THE EFFECT OF ACTIVATED CARBON PARTICLE SIZE ON GOLD CYANIDE ADSORPTION AND ELUTION

by

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SUPERVISORY COMMITTEE APPROVAL

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I have read the thesis of Francis Elnathan in its final form and have found that (1) its format, citations, and bibliographic style are consistent and acceptable; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the supervisory committee and is ready for submission to The Graduate School.

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ABSTRACT

The effect of particle size on gold adsorption and elution from activated carbon has been studied in alkaline solution, in order to understand the nature of gold losses on fine activated carbons, to improve the rate of gold recovery, and to develop an innovative way of treating preg-robbing gold ores. Four stripping techniques (atmospheric Zadra, syringe and press, syringe pump, and filter press elution methods) have been used to evaluate the effect of particle size, temperature, pressure, and strip solution composition on the desorption of gold cyanide from activated carbons. The atmospheric Zadra elution method was studied as a batch process using continuous (without solution replacement) and incremental solution replacement methods at atmospheric pressure and elevated temperatures. However, in the other three stripping methods, pressure was employed to force strip solutions through a bed of carbon placed in a syringe or filter press. In general the rates of adsorption and elution were found to increase with a decrease in particle size as expected. However, in the case of atmospheric Zadra stripping there were some anomalous results which seem to be related to the experimental procedure used. Preg-robbing ore was received, prepared, and leached using fine magnetic activated carbon (MAC) after which the MAC particles were separated by a wet high gradient magnetic separator. In this way almost 70% of the gold was recovered in less than 6 hours compared to previous CIL results, which indicated that about 55% of the gold could be recovered in 24 hours using granular activated carbon.

In summary, it has been substantiated from this research that particle size, temperature, pressure and composition of the strip solution used in the elution process are factors that are interdependent in the influence they have on the elution of gold cyanide from activated carbons. These factors must all be set at their proper levels in order to maximize the rate and amount of gold desorbed from the loaded carbons. Finally, it has been shown that fine activated carbon particles can be loaded and stripped with ease and have some potential for the treatment of preg-robbing gold ores.

TO GOD THE FATHER, GOD THE SON, AND GOD THE HOLY GHOST

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CHAPTER 1

ACTIVATED CARBON CHARACTERISTICS, PRODUCTION AND UTILIZATION

1.1 Introduction

Activated carbon (AC), also called activated charcoal or activated coal, is a general term that covers carbon material derived from charcoal or carbon-based materials. For all three variations of the name, "activated" is sometimes substituted with "active". By any name, it is a black material with an exceptionally high surface area (1, 2). Activated carbon has very important applications in industry, particularly for the recovery of gold in cyanidation plants. However, gold losses on fine activated carbons and the attendant high carbon inventories are quite substantial. Typically, granular activated carbon (GAC) is used by the gold industry, which accounts for long retention times and substantial inventories. If fine activated carbon could be used, it is expected to improve adsorption rates; lower retention time and as a result reduce cost. The treatment of preg-robbing ores with fine activated carbon might also be possible. The focus of this research is to determine the effect of activated carbon particle size on gold cyanide adsorption and elution, and how the stripping of fine carbon might be possible, including consideration of fine magnetic activated carbon (MAC).

1.2 Activated Carbons (AC)

The term activated carbon in its broadest sense includes a wide range of cryptocrystalline graphitic materials prepared to exhibit a high degree of porosity and an extended intraparticulate surface area. These are obtained by thermal decomposition and partial combustion of various carbonaceous materials such as bituminous and anthracite coal, coconut shells, flour and sugar (3).

Active carbon is therefore a processed carbon material with a highly developed porous structure and a large internal specific surface area. Activated carbons may be granular or in powdered form. They consist principally of carbon (87-97%), but also contain elements such as hydrogen, oxygen, sulphur and nitrogen, as well as various compounds originating from the raw material or generated during production. Active carbon may also contain various useless mineral substances in quantities of 1-20%. However, these substances are often removed, and the ash content for commercial AC decreases to between 0.1-0.2% (3, 4).

Activated carbons are excellent adsorbents and thus are used to purify, decolorize, deodorize, dechlorinate, detoxify, filter, and concentrate substances for recovery; they are also used as catalysts and catalyst supports. These applications of active carbons are of interest to most economic sectors and concern areas as diverse as the food, pharmaceutical, chemical, petroleum, mining and metallurgy, nuclear, automobile and vacuum industries. In addition, activated carbon is used extensively in the treatment of drinking water, industrial and urban wastewater, and air and gas. Nearly 80% (220,000 tons/year) of the total active carbon used in the U.S is consumed for liquid phase

applications where both the granulated and the powdered forms of active carbon are used (3, 5).

1.3 Characteristic Features

Active carbons are characterized by their cryptocrystalline graphitic structure (6), and strong adsorption capacity, which occurs mostly in cavities of molecular dimensions called micropores, actually of nanometer size. The characterization of activated carbons is carried out on the basis of several physical and chemical properties, commonly including their surface area, pore size distribution, impact hardness, and ability to adsorb several selected substances such as benzene, carbon tetrachloride, nitrogen from the gas phase as well as iodine, molasses, phenol, and methylene blue from the aqueous phase. The nitrogen BET value of surface area is based on measurement of nitrogen adsorbed as a molecular layer. Typically, nitrogen BET surface area values are found to be between 400 and 1500 m^2/g, the former representing low-activity carbons and the latter high-activity carbons (3, 4).

However, surface area measurements alone are not sufficient to characterize a carbon product since the nitrogen molecule is very small and can penetrate into pores which are not available for larger molecules. The accessibility of larger molecules that are involved in the actual use of activated carbons may be less than that available for nitrogen adsorption. Furthermore, the adsorption of nitrogen carried out at very low temperature (-195°C) cannot measure some of the extremely ultra fine micro capillary pores (3, 4).

The ability of active carbon to arrest different molecules at the inner surface makes it a very powerful adsorbent. The adsorption of molecules from solution is strongly dependent on the porous nature of the activated carbon. This arises from the fact that mass transfer through the carbon pores limits the rate at which a carbon can adsorb any species. The pore volume of active carbon usually exceeds 0.2 cm^3/g but in many instances it is greater than 1 cm^3/g. The single structural factor that results in the adsorptive properties of activated carbon is the extensive pore structure. The pore size distribution depends on the type of raw material and the conditions of manufacture .The International Union of Pure and Applied Chemistry has classified the pore size of activated carbon as follows; micropores have dimensions less than 1.6 nm, mesopores have dimensions between 1.6 and 200 nm, while macropores have dimensions exceeding 200 nm (4, 6, 7, 8, 9, 10, 11).

1.4 Production

The manufacture of activated carbons involves two main steps: the carbonization (pyrolysis) of the carbonaceous raw material at temperatures below 800°C in the absence of oxygen followed by the activation (gasification) of the carbonized product. Thus all carbonaceous materials can be converted into activated carbon; however, the properties of the final product will to a larger extent depend on the nature of the raw material used, the nature of the activating agent, and the conditions of the activation process (3).
The most commonly used source materials are wood, peat, coconut shells, bituminous coal, anthracite coal, fruit pips, rice husk, flour and sugar. Among the raw materials still used in actual commercial production are coconut shells, sawdust and wood char, coal

and petroleum coke, bone char, molasses, peat, and paper-mill waste (lignin). The type of source material has a marked influence on the physical structure of the product; in particular, the pore volume and particle size distribution. For example, wood is used as the source material for decolorizing carbons, whereas coconut shells and coal based carbons are generally used for the gas phase adsorption and gold-recovery applications (5, 6).

1.4.1 Carbonization

Carbonization (or pyrolysis) involves thermal decomposition of the carbonaceous material, eliminating noncarbon species and producing a fixed carbon mass and a rudimentary pore structure. During the carbonization process which takes place in rotary kilns and at temperatures below 800°C in a continuous stream of an inert gas; most of the noncarbon elements such as oxygen and hydrogen are eliminated as volatile gaseous products by the pyrolytic decomposition of the starting material. Many of the impurities are removed as gases such as carbon monoxide, carbon dioxide and acetic aid, or remain as tar-like residue on the carbon. The residual carbon atoms group themselves into sheets of condensed aromatic ring systems (graphitic structures) which are planar and irregular, and as a result have interstices between them which give rise to pores. It must be noted that carbonization in itself does not give rise to a product that has a high adsorption capacity because of the poorly developed pore structure and low surface area. The product produced during the carbonization process is called char, and normally has specific surface area between 10-500 m^2/g, a majority of which is due to micropore formation (3, 5, 6).

1.4.2 Activation

The objective of the activation (or gasification) process is to enhance the pore volume and to enlarge the diameters of the pores which were created during the carbonization process and to create some new porosity as well. Thus activation consists of exposing the carbonized material to an oxidizing atmosphere of steam, carbon dioxide and/or oxygen at temperatures of 700-1000°C to burn off the tar-like residues, and to develop the internal pore structure, which is microporous in nature. Further reaction results in partial or complete burn out of carbon layers, producing a widening of existing pores or the formation of large-sized pores, and exposing the surfaces of elementary graphite crystallites formed during carbonization, which increases macroporosity. Thus the extent of burnoff of the carbon material is a measure of the degree of activation. According to Dubinin and Zavarina, a microporous active carbon is produced when the degree of burnoff is less than 50% and macroporous active carbon when the extent of burnoff is greater than 75%. When the degree of burnoff is between 50 and 75%, the product has a mixed porous structure and contains all types of pores. The activation reaction occurs in two steps. In the first step the disorganized carbon is burned out preferentially when the burnoff does not exceed 10%. This results in the opening of the blocked pores. In the second stage, the carbon of the aromatic ring system starts burning, producing active sites and wider pores. Activation with carbon dioxide promotes external oxidation and development of larger pores compared to activation with steam (3, 5).

1.5 Use of Activated Carbon in Gold Processing and Its Limitations

Activated carbon has found important applications in the extractive metallurgy of gold. During 1999, the amount of activated carbon purchased for gold recovery in the USA and the rest of the world was estimated to be 4 thousand and 7 thousand metric tons respectively, which represents sales on the order of $8 million and $14 million respectively (12).

Carbon adsorption is a common method of removing many dissolved species from solution. In particular, carbon adsorption is used extensively in removing low levels of many types of dissolved ions from solution (13). The introduction of cyanide leaching almost a hundred years ago revolutionized the treatment of gold ores and allowed gold to be recovered from ores that could not be amalgamated or concentrated by gravity. Major milestones have since been realized in the following areas:

- The use of activated carbon to collect gold from solutions by CIP, CIL and CIC techniques
- Electrowinning of gold from pregnant solutions
- Oxidation pretreatment to make carbonaceous gold ores amenable to cyanidation
- The application of heap leaching to low-grade ores.

The use of activated carbon for gold recovery is in common practice and widely used today, but 35 years ago if the gold-ore was not high-grade and amenable to treatment in the standard countercurrent decantation cyanide mill with zinc precipitation, there were no processing options (5, 7, 14, 15, 16, 17, 18).

By replacing the Merrill-Crowe zinc cementation step, carbon-in pulp (CIP) and carbon-in-leach (CIL) recovery provided a process that allowed for the treatment of lower

grade and problematic ores at lower capital and operating costs and higher metal recoveries (19). Today, CIP and CIL are the predominant recovery methods in use, accounting for approximately 42% of worldwide production (10).

The activated carbon adsorption process did not receive much attention as an alternative to the Merrill-Crowe process until the last part of the 20^{th} century, when several factors led to further consideration of the carbon adsorption technology. First, suitable methods were developed for the elution of gold from activated carbon which could then be regenerated and recycled, making the process more cost-effective. Second, the carbon-in-pulp process became generally accepted by industry to eliminate the costly filtration and countercurrent thickening steps usually encountered in gold cyanidation plants (20).

In the gold industry, activated carbon is most often used to adsorb low levels of gold from alkaline cyanide solutions. The gold, dissolved as the $Au(CN)_2^-$ complex, is recovered from solution by methods such as the carbon-in pulp (CIP), carbon-in-leach (CIL) and carbon-in-column (CIC) processes. Activated carbon is often utilized in a countercurrent manner to maximize adsorption (5, 21, 22).

The adsorption of gold cyanide from solution by activated carbon is a process that is well understood unlike the desorption process. Countercurrent processing allows the carbon with the least amount of adsorbed gold to contact the solution that is most depleted, whereas the carbon that is nearly loaded contacts the solution that has the highest concentration of gold to be adsorbed. After separation of the activated carbon from the pulp or solution, the adsorbed $Au(CN)_2^-$ complex is stripped from the activated

carbon at elevated temperatures (greater than 90°C) using a stripping solution that often contains 1% NaOH and some NaCN (5, 12, 13, 21, 22).

A global survey of 36 gold producing companies indicated that the average carbon consumption was 0.01 kg/t of processed ore (23). Due to the potential loss of gold on fine carbon, most gold-producing companies employ a method to recover part of the fine carbon. Once the carbon fines have been collected, the industry practice is to stockpile or ship the product offsite to be processed by an 'ash method'. The average cost of shipping and processing by the ash method is very high (23, 24, 25). Conventional activated carbon circuits for gold recovery use granular (2.8 x 1.4 mm) activated carbon particles that are significantly coarser than the ground ore in order to produce an effective separation of gold-loaded activated carbon from the slurry phase by mechanical screening. While effective, the carbon adsorption process has some inefficiencies. Some of the problems include slow rates of adsorption, high plant carbon inventories, gold losses, generation and loss of fine carbon. First, the carbon losses can be as high as 50 grams of carbon per metric ton of ore, and cumulative losses of fine activated carbon within a year of operation can be as high as 20% of the total carbon inventory. Of course, both the carbon and associated gold are lost from the plant operation. The second issue is that, granular activated carbon has a slow rate of gold adsorption and low effective loading capacity compared to powdered activated carbon. Furthermore, the gold adsorbed on the lost carbon is permanently lost, results in the expenditure of additional resources (such as ore reserves, energy and refuse disposal areas) to replace the lost gold values. Magnetic powdered carbon offers a unique solution to this problem (12, 21, 26).

1.6 Magnetic Activated Carbon (MAC)

Magnetic activated carbon (MAC) patented by the University of Utah in 1999 offers a unique solution to the problems associated with granular activated carbon for the adsorption of gold cyanide from aqueous solution. By making the activated carbon magnetic, it can be separated from solution, even if the solution contains a significant concentration of solids, using a wet magnetic separator, as opposed to the traditional screening technology (26).

1.6.1 Importance of MAC

MAC has the potential of replacing AC in all its applications. It has the potential of offering technical, economic and social benefits to the public and the mining industry. Some of the anticipated benefits would include, improved process kinetics, lower capital and operating costs, higher gold recovery due to reduced gold losses arising from minimized 'preg-robbing' compounds, reduced carbon losses due to attrition and reduction in environmental impact (9, 26, 27, 28).

1.6.2 Production of MAC

Production of MAC requires two main components: a carbon source and an iron precursor (27, 28). The carbon source can be from any organic matter such as hardwood, softwood, flour, sugar and rice husk. The iron precursor may be any iron salt such as iron citrate, iron oxalate or iron sulphate. The iron precursor is combined with the carbon source prior to carbonization (pyrolysis) by either mixing or impregnation.

The mixing procedure is employed when the particle size of the carbon source and that of the iron precursor are comparable; for example flour and powdered iron salt. Mixing is normally carried out until homogeneity is achieved. Impregnation, on the other hand, is used for materials that do not melt at the high pyrolysis temperatures such as hard and soft woods. When the carbon source can form a melt, as in the case of flour, then the iron salt can be completely incorporated into the activated carbon matrix. However, when the carbon source does not form a melt, then impregnation is the only option presently available to be use. The iron source is dissolved in water and the carbon source soaked in the iron solution for a specified period of time.

The homogeneous mixture of the iron and carbon sources is then pyrolyzed at a temperature of about 1000K in the presence of nitrogen gas to burn off volatile materials. The char matter from the carbonization process is activated in a carbon dioxide atmosphere at about 1200K to give the material the porosity and surface characteristics needed for optimum adsorption. By activating in the carbon dioxide atmosphere, the iron precursor is converted to magnetite.

The conversion of the iron precursor to magnetite produces a product that exhibits soft magnetic properties, making it possible to recover MAC from slurry streams using a magnetic separator. A soft magnet is material that exhibits magnetic properties when it is subjected to a magnetic field, but loses its magnetic properties when removed from the magnetic field. The advantage of this product over conventional granular activated carbon (GAC) is that the fine MAC can be separated from the slurry using a magnetic separator rather than using screens (12, 21, 26, 27, 28).

1.7 Gold Adsorption by Activated Carbon

The complex physical and chemical structure of activated carbons allows the adsorption of different species by various mechanisms. Consequently, the exact mechanism of adsorption of gold from cyanide solutions has been difficult to determine. Several mechanisms have been advanced by different investigators to explain their findings, and as result a clearer picture has emerged over time. Significantly, investigations using the Mossbauer spectroscopy, X-ray photoelectron spectroscopy and model extractants on high ionic strength solutions have shown that the gold cyanide complex is adsorbed predominantly as an ion pair. Further evidence for this has been provided by surface chemical, and other, analyses which have established that the oxidation state for gold adsorbed by carbon is +1. The mechanism is best described by the equation below:

$$M^{n+} + nAu\,(CN)_2^- = M^{n+}\,[Au\,(CN)_2^-]_n\,(ads) \qquad (1)$$

where the ion pair, $M^{n+}[Au\,(CN)_2^-]_n$, is the adsorbed gold species (5, 22). Work done by Munoz et al indicates that the same gold adsorption phenomenon is expected to occur in MAC as in AC. In addition, the group has established that the adsorption rate of AC increases as its particle size decreases (12, 28).

1.8 Elution of Adsorbed Gold Cyanide from Activated Carbons

Activated carbon that has been loaded with gold and other metals in adsorption processes must be treated by an elution step to desorb the metals from the carbon. This

produces a smaller volume of high-grade gold solution, suitable for final gold recovery by electrowinning or zinc precipitation, and allows carbon to be recycled to the adsorption circuit. Carbon is typically reused between 100 and 400 adsorption-elution cycles, depending on the carbon quality and the effectiveness of the carbon regeneration process. The desorption process, commonly referred to as either elution or stripping, is a reversal of the adsorption process. The chemical and physical factors that do not favor adsorption generally tend to favor the desorption process. In the case of gold adsorbed from cyanide solutions, the stripping reaction is most simply represented by (22):

$$M^{n+}\,[Au\,(CN)_2^-]_n(ads) = nAu\,(CN)_2^- + M^{n+} \qquad (2)$$

Temperature is the most important factor in the elution of gold cyanide from carbon. It is possible to reduce elution times substantially by operating at temperatures greater than 100°C; however, this requires the use of elevated pressures. Elution systems have basically evolved into two classes:

- Processes that operate at atmospheric pressure and temperatures less than 100°C
- Processes that operate at elevated pressures to allow for stripping at elevated temperatures greater than 100°C, in order to achieve faster elution rates.

There are currently several elution systems developed and used commercially including:

- Atmospheric Zadra Stripping
- Pressurized Zadra Stripping
- Anglo American Research Laboratory (AARL) Stripping

- Alcohol Stripping
- Micron Elution Process
- Davidson Stripping Method

Significant progress has been made in understanding the nature of gold adsorption from alkaline solutions by activated carbons, in particular its adsorption rate and capacity. Also, considerable research has been reported for the study of the industrial applications of the elution process. However, the amount of research devoted to the fundamental study of elution is rather limited with the nature of the stripping reaction not very well understood. In particular, the effect that activated carbon particle sizes have on the stripping of adsorbed gold cyanide is not well documented. It is well known in the gold industry that substantial gold losses on fine carbons decrease the recovery. Consequently high carbon inventories of granular activated carbon must be maintained due to slow adsorption/desorption kinetics and due to attrition and abrasion by carbon-on-carbon and carbon-on-screen respectively. So the focus of this thesis research is on the effect that different particle sizes of activated carbon have on the adsorption and desorption of gold cyanide by the Zadra Elution Method, Davidson Stripping Method and Anglo-American Research Laboratory Method.

Atmospheric elution of adsorbed gold cyanide from activated carbon with cyanide and caustic soda is known as the atmospheric Zadra process. The atmospheric Zadra process consists of circulating a solution containing approximately 1-2% sodium hydroxide and 0.1-0.5% sodium cyanide at atmospheric pressure, temperature of 95°C and a flow rate of 2 bed volumes (bv)/hr through a stationary bed of loaded carbon. Gold that was previously adsorbed on the carbon as the sodium, potassium or calcium gold

cyanide ion pair is desorbed from the carbon by a reversal of the adsorption kinetics. The gold is then recovered from the pregnant strip solution by electrowinning onto steel wool. The gold depleted solution is then reheated and recycled to stripping for reuse. The process generally takes between 48 and 72 hour to elute loaded carbon to a low residual loading of less than 100 g/t. In the Pressure Zadra process, stripping is carried out both at elevated pressure and temperature (5, 16, 17, 22).

Davidson observed that gold could be eluted from activated carbon after pretreatment of the gold-loaded carbon with certain metal carbonates before elution with hot water low in calcium content. The alkali carbonates of potassium, lithium and sodium were found to be most effective. Davidson optimized conditions for the maximum recovery of gold from the carbon surface and found that a pretreatment with a solution containing 5% potassium carbonate and 10% potassium hydroxide followed by elution with hot water at 90°C could recover 99% of loaded gold in 12 bed volumes and almost all of it in 22 bed volumes (3, 29).

In the AARL method, the carbon loaded with gold is washed in dilute mineral acid, then washed in DI-water, and soaked for about 30 minutes in 3% NaCN and 2% NaOH solution. The loaded carbon is then stripped with DI-water at elevated temperatures (15, 22).

1.9 Cyanidation and Recovery of Gold from Preg-robbing Ores

Gold recovery from certain ores (carbonaceous ores) by cyanidation is limited by the presence of naturally occurring carbonaceous materials, which tend to adsorb the gold from the alkaline cyanide solution unless steps are taken to prevent this adsorption

reaction from occurring. Such ores are most often referred to as preg-robbing ores. Carbonaceous ores contain carbonaceous components that adsorb dissolved gold during leaching, thereby reducing extractions by cyanidation (30). Important examples are found at Ashanti and Prestea (both in Ghana), Carlin and Jerritt Canyon (both in Nevada, USA), Witwatersrand (South Africa), and various Western Australia ore deposits. Fractionation and characterization of carbonaceous ores from Carlin, Prestea, and Natalinsk and Bakyrchik (Russia) suggested that such carbonaceous matter consists of three components: hydrocarbon, humic acid and activated elemental carbon. According to Sibrell et al, the major component of organic matter in the Carlin ores is activated carbon-type compounds; humic acids were not found in the organic matter (31). However, the exact nature of the components is not well established, and variations in carbon activity are great (22, 32).

It should be mentioned that a wide variety of other minerals, including copper-sulphide minerals, clays and silicates can adsorb gold depending on their surface area and surface characteristics. Also worthy of mention is the fact that the presence of carbonaceous matter in an ore does not necessarily result in poor gold recovery (33, 34). Improved understanding of preg-robbing is essential for increasing gold recovery. Carbonaceous matter in gold ore has been shown to act like activated carbon and adsorb solubilized gold from cyanide solution during leaching. It is thought that the dispersion of the carbonaceous matter and its fineness (less than 20 μm) account for the high adsorption and loss of gold during cyanidation (17, 32, 34, 35, 36).

Preg-robbing of carbonaceous ores can be overcome by a number of techniques including:

- Use of gold adsorbents (activated carbon or resins) to compete with the carbonaceous material
- Deactivation or Passivation by oxidation- roasting, chemical and biochemical oxidation (34, 37)
- Use of surface-blinding agents-partially effective (37, 38, 39).

Presently, the oxidative pretreatments of carbonaceous ore are the most effective processes. However, the mineralogy of the ore and specific characteristics of the carbonaceous material should be analyzed in other to determine the most appropriate methods for treatment (30). One of the thesis research objectives is to consider the use of MAC for gold recovery from preg-robbing ore by the carbon-in-leach process (CIL). And so the CIL process for the treatment of preg-robbing ores is briefly mentioned.

The CIL approach for the treatment of preg-robbing ores uses a stronger adsorbent (such as AC, MAC or Resin) for gold cyanide, which competes with the carbonaceous material in the ore. The efficiency of the AC used to compete with the naturally occurring carbonaceous material depends on its gold-adsorption capacity, which may be two orders of magnitude higher than that of the natural carbonaceous matter. In a mildly carbonaceous Carlin ore, around 70% of the gold was recovered by a CIL process in comparison with 15% gold recovery without AC (21, 34, 37). Generally, using AC in the cyanidation of preg-robbing ores improves the gold extraction, however, this depends on the mineralogy of the ore and the amount of the adsorbents added (30). The CIL process, though effective in the treatment of preg-robbing ores by AC, has some limitations. The first concern is carbon losses caused by breakage of granular carbon. The duration of AC in the CIL process which is normally about 24 hours, and the screening of

the AC after the loading process tend to break the carbon through abrasion and attrition. Another limitation is that gold loaded on the fine AC is also lost to the tailings in the process

Preliminary research results at the University of Utah's Department of Metallurgical Engineering suggest that MAC not only resolves the limitations of AC in the CIL process for the treatment of preg-robbing ores, but also addresses problems encountered in other applications of AC (26, 28). For example, the problem of gold losses by attrition is avoided since the MAC is already in powdered form and can stay in the pulp for longer time periods. MAC also reduces the possibility of gold adsorption by carbonaceous matter due to its rapid rate of gold adsorption (12, 21, 26, 28, 30). Research is in progress in this area and this thesis research considers the application of MAC to preg-robbing ores.

1.10 Research Objectives

The objectives of the thesis research are:

- To investigate the effect of activated carbon particle size and other process variables on gold cyanide adsorption and desorption by the Zadra, Davidson, and Anglo-American Research Laboratory elution methods.
- To compare the elution kinetics of AC and MAC
- To investigate the use of MAC for the recovery of gold from preg-robbing ores.

CHAPTER 2

MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Characterization of AC/MAC

To gain an understanding of the effect different particle size fractions of AC/MAC have on the adsorption and elution of gold cyanide, AC/MAC properties such as attrition resistance and specific surface area of all the carbons used were also determined. Experimental materials and procedures are presented in this chapter.

2.1.1 Source of Activated

Activated carbons used in the thesis research were supplied by companies listed in Table 1 according to source and particle size of the carbons received.

Table 1
Activated Carbon Samples.

Carbon Sample/Source	Particle Size
BMAC 27B (Magnetic AC) / Eriez Magnetics	191 x 49μm
Barnebey / Newmont Mining	2.8 x 1.4 mm
Calgon / Eriez Magnetics	2.8 x 1.4 mm
Calgon GRC 22 / Calgon Corporation	2.8 x 1.4 mm

2.1.2 Attrition Resistance Measurements

Attrition resistance measurements are used to measure the ability of carbon to withstand breakage in its applications; in particular, in the gold industry. The attrition resistance of carbons used in this thesis research was determined by bottle-rolling a known amount and size fraction of carbon in a specific volume of DI-water for 24 hours, after which the undersize material generated was used to calculate the attrition resistance (40, 41).

Granular carbon (2.8 x 1.4 mm and weight 120 g) was tested for attrition resistance by wet-screening samples on 2.80 x 1.981 mm screens. Particles of carbon on the 1.981 mm screen were then thoroughly washed with DI-water to rid them of dust and fines. The sample was dried in an oven at 110°C overnight, removed and cooled in a dessicator. Fifty grams (50 g) each of the dried and cooled carbon sample was measured into 1 liter plastic bottle. Then 100 ml of DI-water was added to each sample in the bottle and rolled at 40 rpm for 24 hours on rollers.

After 24 hours, the content of each bottle was poured onto the 1.981 mm screen set over a 2 liter beaker and washed thoroughly with DI-water. The undersize from each of the samples in the beaker was filtered through a filter paper (noting its mass), dried overnight at 110°C in an oven, cooled to room temperature in a dessicator, and weighed. Also dried and weighed were the carbon particles remaining on the screen. The weight of each filtered sample was made to determine the weight of the fines generated during the rolling period. The mass balance for the carbons before and after the bottle-roll test, percent attrition for each test, and the mean percent attrition for each sample (two tests were conducted for each sample) are presented under results and discussions. The

procedure for determining the attrition resistance for BMAC 27B was the same as already described above for Barnebey and Calgon carbons except for the following modifications: The BMAC 27B (49 x 191 μm) sample, was sieved through a 45μm sieve and the oversize fraction of +45 μm was used for bottle-roll test. DI-water of 200 ml was added to the carbon sample in the bottle roll test. The percent attrition for each test as well as the average percent attrition for the sample was also calculated for BMAC 27B.

2.1.3 Specific Surface Area Determination by BET

The specific surface areas of the different size fractions of Calgon activated carbon and BMAC 27B carbon samples were determined by the BET method using a Micromeritics Accelerated Surface Area and Porosimetry (ASAP) Analyzer model 2010. The carbon samples analyzed were BMAC 27B (191 x 49 μm) and Calgon carbon supplied by Eriez Magnetics. Another sample of Calgon carbon, GRC 22, of Sri-Lankan origin, supplied by Calgon Corporation, was also analyzed. Samples of these carbons, pretreated and sized into fractions of 2.80 x 1.40 mm, 850 x 425 μm, 425 x 212, 212 x 45 μm and minus 45 μm for adsorption and elution tests were taken for the BET analysis. Four sets of the sized fractioned carbon samples were taken for the BET test; three sets taken from the Eriez Magnetic carbons and one set from Calgon Corporation. A set consisted of the different particle sizes of carbon and BMAC 27B. The specific surface area of the set of carbon samples from Calgon Corporation was determined with and without gold loading from cyanide solution. With the samples from Eriez Magnetics however, the specific surface area of one set of carbon samples was determined without

gold loading, another set was determined with gold loading, while the last set was determined with gold stripped from the carbons.

About 0.1g of each sample was measured into a sample tube and pretreated by degassing the sample at 350°C and vacuum pressure of 5 μmHg for at least 4 hours to remove any adsorbed contaminants and moisture. The sample was transferred from the degassing port to the analysis port where it was cooled to cryogenic temperature and analyzed at liquid nitrogen temperature with nitrogen as the adsorbate for at least 3 hours. A relative pressure range of 0.001-0.250 was used. Nitrogen gas was used for degassing, backfill and analysis of the sample (42, 43).

2.2 Adsorption Procedures

Chemicals used in the thesis research were all of reagent or analytical grade and the water used was deionized (DI) water unless stated otherwise. The adsorption capacities and adsorption rates of all carbons used in the research were determined by procedures described in the following sections; and have been the standard procedures for all subsequent adsorption tests conducted during the course of this research. Figure 1 depicts the experimental set-up for adsorption experiments.

2.2.1 Adsorption Capacity

The gold adsorption capacities (K- value) of all the activated carbons (including BMAC 27B) were determined. Gold adsorption capacity gives the gold loading on the carbon in equilibrium with 1 ppm gold solution after 24 hours contact time; and AC

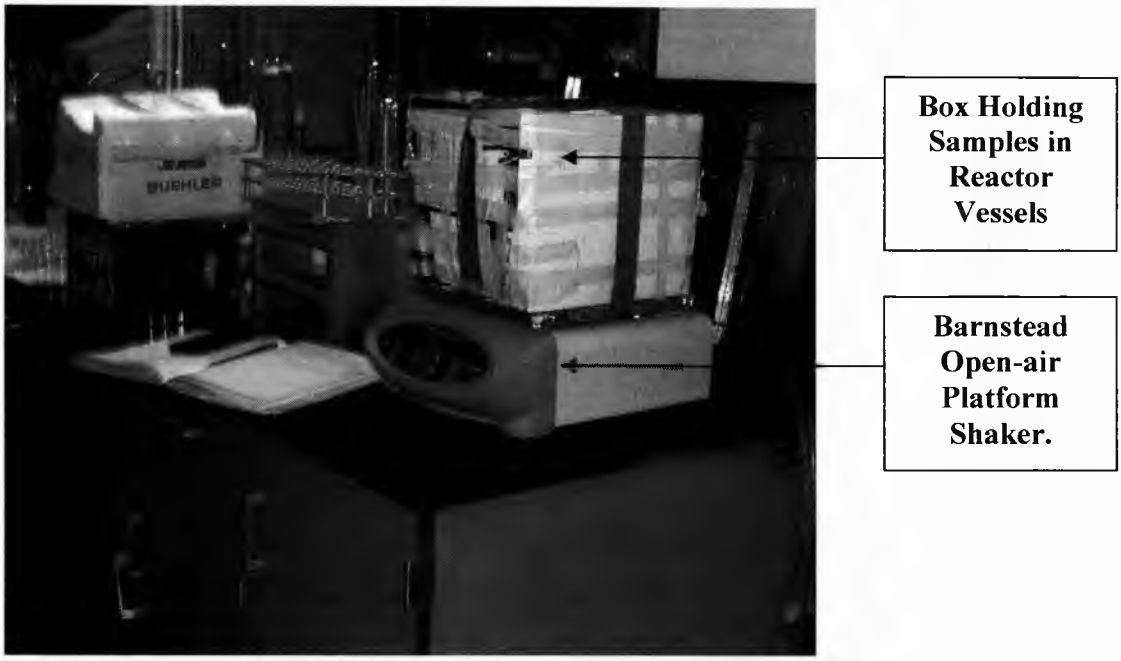


Figure 1 Adsorption Capacity and Adsorption Rate Experimental Set-up.

samples effective for gold loading should have a K-value greater than 25 kg Au/t C (40, 41). The AC's used were washed thoroughly to remove all fines and dried overnight at 110°C in a Stabil-Therm Gravity oven.

The samples were then removed and placed in a desiccator for cooling to room temperature and storage until ready to be used. A 100 mg per liter of solution, as gold, was used in the adsorption capacity experiments. In the preparation of 100 mg Au per liter of solution, a 1L borate buffer solution was first prepared, in which 3.09 g of boric acid and 3.73 g of potassium chloride were weighed into a 1L beaker. About 500 ml of DI-water were added to the beaker and stirred. A mass of 2 g of NaOH was added to the contents of the beaker to adjust the pH to between 10 and 11. Then 0.1462 g of $KAu(CN)_2$ was added to the borate buffer and stirred thoroughly to obtain homogenous

mixture. The content of the beaker was then transferred to a 1L volumetric flask and more DI-water was added to make 1L of 100 mg/L Au solution required for the adsorption capacity test. A mass of 200 mg of NaCN was dissolved in the solution prior to use. A sample of this solution was taken for gold analysis to determine the initial concentration of the stock solution.

Masses of 0.1, 0.2, 0.3, 0.4, 0.5 g from each of the cooled active carbon samples were weighed into 250 ml plastic reactors. Each sample in the plastic reactor was contacted with 100 ml of the 100 mg of Au solution on a Barnstead Laboratory shaker for 24 hours at 25°C; while the shaker speed was set at 200 revolutions per minute. After the shaking cycle was completed, the carbon in each vessel was filtered off under vacuum using a Whatman filter paper. A 20-30 ml sample of the filtrate from each reactor vessel was stored in sample vials for gold analysis by a Plasma-400 ICP-AES [inductively-coupled plasma (ICP) - atomic emission spectrometer (AES)] instrument. From the ICP solution analysis, the gold adsorbed by the carbon in each case was determined by the difference in gold concentration before and after adsorption multiplied by the volume of gold cyanide solution used. Calculations are shown in the appendices. A five-point isotherm (from the five carbon masses) plotting gold adsorbed versus the residual equilibrium concentration was then prepared.

From the isotherm the gold equilibrium constant (K-value) was determined, using the Freundlich isotherm:

$$X/M = [KC]^{1/n} \qquad (3)$$

where the X/M value defines the mass of gold (mg) adsorbed on the carbon (g). Therefore the loading capacity, K-value is defined as the carbon-loading (mg Au / g C) in equilibrium with a residual gold concentration of 1 ppm as determined from a plot of the isotherm (40, 41).

2.2.2 Fire Assay and Scanning Electron Microscopy (SEM)

Fire Assay and SEM imaging were useful analytical techniques employed to help the research effort. Loaded carbon samples to be eluted and stripped carbon samples after elution were sent to Newmont Metallurgical Laboratory for fire assaying and SEM analyses. SEM images of unloaded, loaded and stripped AC were also taken at the University of Utah. Data obtained are presented in Chapter 3, Results and Discussion.

2.2.3 Adsorption Rate

Gold adsorption rates of AC (including BMAC 27B) were also determined. Usually, the percentage gold adsorbed by 1 g of carbon from 10 mg/L gold solution in 1 hour should be greater than 60% (40, 41).

Activated carbons used were washed thoroughly to remove dust and fine particles. Carbon samples were then dried at 110°C overnight in an oven to a constant mass. Samples were removed from the oven and stored in a desiccator to cool. A lower concentration of gold solution, 10 mg Au per liter of solution was used for the test. A 0.2769 g amount of $CaCl_2$ and 0.2503 g amount of KCN were measured into a 1L beaker containing about 0.5L of DI-water and stirred thoroughly to ensure complete dissolution of the reagents. A 0.015 g amount of $KAu(CN)_2$ was further dissolved in the beaker and

the contents transferred into 1L volumetric flask and more DI-water was added to the flask to make up the 1L gold solution required for each test. A mass of 1 g of each pretreated carbon sample was measured into 1.2 L stoppered plastic containers for the rate test. One liter of 10 mg gold solution at a pH between 10 and 11 was measured into each plastic reactor (standing upright on the shaker shown in Figure 1) containing carbon samples and the time was noted.

The plastic containers holding the carbon samples in contact with gold cyanide solution were then shaken for 60 minutes. During the shaking cycle, 10ml samples were withdrawn and filtered into vials from each plastic container at 0, 15, 30, 45 and 60 minutes for gold analysis by ICP-AES. From the results of the ICP solution analysis; the quantity of gold (Q in %) adsorbed by the carbon was calculated at each time interval using equation 4:

$$Q = \{[A - B]/ A\} \times 100 \quad (4)$$

where

A = Initial gold concentration in (mg/l)

B = Residual gold concentration (mg/l) for the time at which the sample was withdrawn

Plots of the rate experiments are shown in Chapter 3. Specific calculations regarding this section can be found in the Appendix.

2.3 Elution Procedures

Gold losses due to the generation of fine activated carbons can be quite substantial. The method currently employed by some companies is to stockpile the fines or ship the fines offsite to be processed; either way is very costly (23, 25). The objective of this research is to investigate the effect that different particle sizes of activated carbon have on the elution of gold cyanide from loaded AC; and whether a cost-effective way of eluting such loaded carbons is possible. The carbon preparation and loading processes as well as the stripping methods used are described in the following sections.

2.3.1 Carbon Preparation and Loading

The procedure used to load the different particle sizes of activated carbons with gold cyanide for subsequent elution experiments is described in this section. Table 2 shows the type of AC, source, and the particle size used in these experiments. Carbon loadings were carried out using the experimental set-up in Figure 1. Granular (2.8 x 1.4 mm) activated carbons received were usually washed several times with DI-water and dried at 110°C overnight in an oven.

Dried activated carbons were then crushed using a mortar and pestle or a ceramic mill depending on the quantity of each sample required. Crushed samples were then wet-screened to 850 x 425 μm, 425 x 212 μm, 212 x 45 μm and minus 45 μm particle size fractions as shown in Table 2. The magnetic AC, BMAC 27B (191 x 49 μm) was used after washing thoroughly with DI-water without undergoing any further size reduction. The screened carbon samples (including BMAC 27B) were again dried overnight at 110°C in the oven.

Table 2
Prepared Activated Carbon Samples by Particle Size.

Carbon sample/source	Particle size
BMAC 27B / Eriez Magnetics	191 x 49 μm
Barnebey / Newmont Mining	2.8 x 1.4 mm
Barnebey / Newmont Mining	212 x 45 μm
Calgon / Eriez Magnetics	2.8 x 1.4 μm
Calgon / Eriez Magnetics	850 x 425 μm
Calgon / Eriez Magnetics	212 x 45 μm
Calgon / Eriez Magnetics	Minus 45 μm
Calgon GRC 22 / Calgon Corporation	2.8 x 1.4 mm
Calgon GRC 22 / Calgon Corporation	850 x 425 μm
Calgon GRC 22 / Calgon Corporation	425 x 212 μm
Calgon GRC 22 / Calgon Corporation	212 x 45μm

Dried activated carbons were then stored in a desiccator until ready to be loaded with gold cyanide solution for any required test. Dried and cooled activated carbons were loaded with gold cyanide solutions of varying concentrations and this depended on the amount of gold loading required for any particular test. Gold loadings therefore have varied from 2.5 to 250 mg Au/ g C. Gold cyanide solution preparation for carbon loadings always followed the procedure described in section 2.2.1. Gold cyanide solutions of any concentration were prepared first by preparing the specific volume of

borate buffer required. This then was followed by adjusting the borate buffer to the required pH (10-11), and then finally dissolving the weight of $KAu(CN)_2$ specific to the concentration required in the buffer solution.

Carbon loadings were always carried out at room temperature by contacting the carbons with potassium gold cyanide solution for 24 hours on a Barnstead open-air platform shaker. Shaker speeds were varied between 180- 220 rpm while maintaining pH values between 10 and 11. A sample of the initial gold cyanide stock solution prepared was always taken for gold analysis by ICP-AES.

After the AC-loading cycle was completed (24 hours), the mixture of AC and gold-depleted solution was filtered, and samples of each filtrate were stored in vials for gold solution analysis by ICP-AES. The difference between the initial quantity of gold in solution and the quantity of gold in the filtrate after the loading process, multiplied by the volume of gold cyanide solution was used to determine the amount of gold adsorbed on each sample of AC for any subsequent processes, such as elution.

Loaded carbons were then usually washed thoroughly with DI- water several times while on the filter paper and then allowed to dry at room temperature under a hood. Loaded, washed and dried carbon samples were stored in sample bottles and used for the various elution tests conducted as described in the following sections. Carbon preparation and loadings for other tests in the research such as Fire assay, BET and SEM followed the procedure described above.

2.3.2 Atmospheric Zadra Elution

The atmospheric Zadra elution method involved stripping the different particle size fractions of loaded activated carbons at atmospheric pressure and elevated temperatures by refluxing the strip solution as shown in Figure 2 (5, 16, 22).

Batch stripping without solution replacement (or batch-continuous stripping method) and batch stripping with incremental solution replace methods were employed. In the batch stripping with incremental solution replacement method, fresh strip solution was used after each sample cycle in the sample's total stripping cycle. However, in the batch-continuous stripping method, a specified volume of strip solution was used for a sample's entire stripping cycle.

In one of the batch-continuous stripping experiments, the strip solution's gold concentration was adjusted to determine the effect of initial concentration on the elution rate. Furthermore, in one of the batch-continuous stripping, air was bubbled continuously into the elution set-up to determine whether gold cyanide is adsorbed on the activated carbon in the reduced form. In the batch-continuous stripping, carbon samples to be eluted were directly submerged in the strip solution in the distillation flask; however, in the batch with incremental solution replacement stripping, carbon samples were placed in thimbles to facilitate fresh strip solution replacement after each sample cycle. Strip solution used in the batch with incremental solution replacement was enough to submerge the carbon in the thimble during elution.

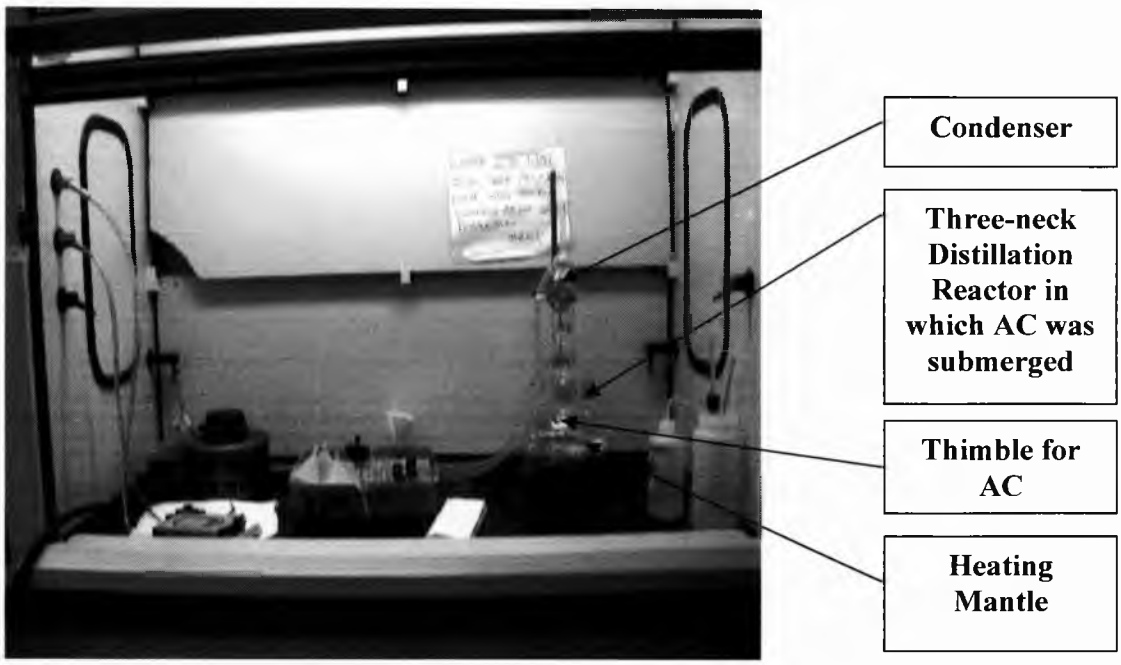


Figure 2 Atmospheric Zadra Elution Set-up for Continuous and Batch Elution.

In both stripping methods, the boiling solution agitated the carbon particles. Stripping time for atmospheric Zadra elution was varied from 1 to 30 hours in some cases. The Zadra solution was made up of 0.5% NaCN, 1% NaOH and pH of between 12 and 13 (5, 16, 22). The temperature of the Zadra solution was maintained at boiling point (98-100^{o}C).

Loaded activated carbons to be eluted were contacted with boiling Zadra solution in a three-neck distillation flask fitted with a condenser. The distillation flask was heated by a heating mantle, while the condenser had cold water running continuously through it condensing the strip solution. The carbon samples in some instances were presoaked for about 30 minutes prior to stripping. Refluxing of strip solution in this closed system was carried out from between 1 to 30 hours depending on the elution time for any set of

samples. Solution samples were taken from the atmospheric Zadra elution set-up at certain time intervals for gold solution analysis by ICP-AES. From these results percentage gold eluted was calculated as a function of time for each size fraction of the loaded carbons. Results to this section are presented and discussed in Chapter 3. Calculations are shown in the Appendix.

2.3.3 Syringe and Hydraulic Press Stripping Method

The syringe and hydraulic press stripping method involved mechanically forcing boiling strip solution through a bed of loaded carbon particles in a syringe as shown in Figure 3. An average pressure of about 42 psi was applied to force the strip solution through the bed of carbon particles at a flow rate of about 13 ml/minute.

A 60 ml syringe fitted with 0.45 μm Whatman (Cat No 6780-2504) Millipore size membrane filter at its lower end and a hydraulic press were used for these stripping experiments. A mass of 1 g of loaded AC was placed in the 60ml syringe fitted at its lower end with 0.45 μm Millipore size membrane filter. The strip solution used was at the boiling point (about 100°C) and made up of 1% NaOH, 0.5% NaCN at pH 12- 13. Each carbon sample fed into the syringe was presoaked for about 30 minutes before the stripping process began. After the presoak, 50 ml of the boiling strip solution increments were fed sequentially through the bed of loaded carbon sample contained in the syringe. This procedure forces the adsorbed gold cyanide from the carbon into the strip solution.

The stripped solutions containing eluted gold were collected in beakers after passing through the Millipore membrane filter fitted at the lower end of the syringe. Samples of the strip solution were taken for gold analysis by ICP-AES.

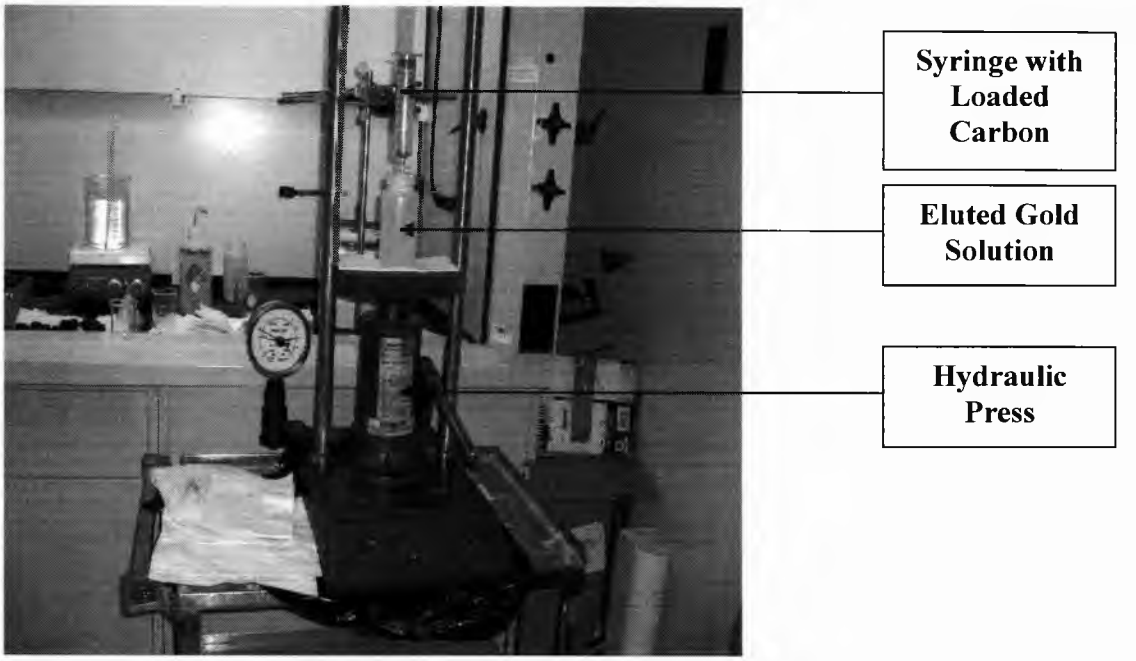


Figure 3 Syringe and Hydraulic Press Elution Set-up.

The volume of sample taken for gold analysis during the stripping process was two-bed volumes or 100 ml of the strip solution. Strip solution samples were thoroughly mixed in stoppered plastic containers and a representative sample taken for gold analysis.

About 200 ml of hot DI-water was forced through each bed of a carbon sample after its stripping cycle to remove any residual gold still present in the carbon bed. A total of about 10-bed volumes of strip solution and 4-bed volumes of hot DI- water were passed through each carbon bed during the stripping process. From the ICP-AES results, the percent Au eluted was determined for each size fraction of the loaded carbons and the results to this section are presented in the Results and Discussion Chapter. Calculations for the section can be found in the Appendix.

2.3.4 Syringe Pump Stripping Method

The syringe pump stripping method involved using the syringe pumping mechanism to force strip solution through the bed of gold-loaded carbons in the syringe as shown in Figure 4. Zadra and Davidson strip solutions were used for stripping gold-loaded carbons under this method. The strip solution flow rate through the bed of carbon in the syringe was noted and the minimum pressure applied to the syringe plunger was calculated from the plunger diameter and force applied to it.

Under the Zadra method, 1 g each of the different particle sizes of the gold-loaded carbons was fed into the 60ml syringe and made into a bed. A 0.2/0.45 μm Millipore size membrane filter was fitted to the lower end of the syringe through which the stripped gold solution passed into beakers. Two experiments were conducted with the Zadra strip solution under this method. One experiment was conducted with the strip solution maintained at 75°C and the other conducted with the Zadra strip solution at its boiling point (98-100°C). The Zadra strip solution had a composition of 1% NaOH, 0.5% NaCN. Eluant was pumped through the bed of carbons in the syringe at a flow rate of between 15/26 ml/minute for the two experiments conducted under the Zadra method.

The strip solution retention time in the syringe depended on the flow rates, and so the retention times of the eluant varied from 2-5 minutes. The carbon samples for experiments were presoaked for a time which varied from 10-30 minutes with 50 ml of strip solution at room temperature prior to the stripping process; and the pH of the strip solutions was 12.8 and 11.0, respectively. The calculated minimum pressure for all experiments conducted with the syringe pump was 36 psi.

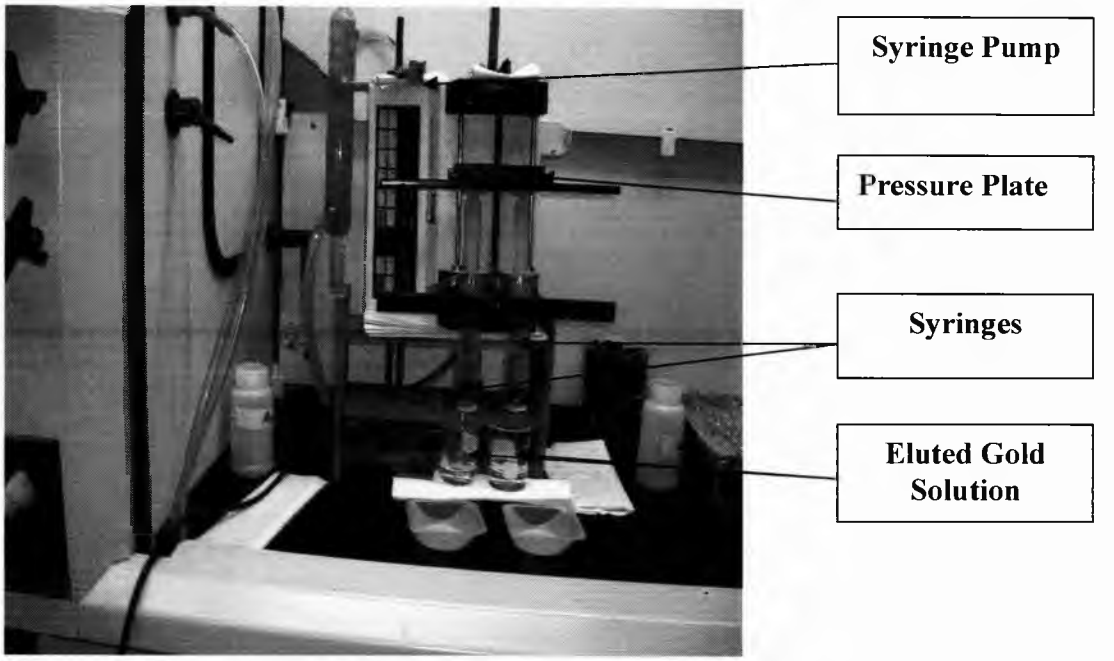


Figure 4 Syringe Pump Elution Set-up.

The stripped gold solution was admitted into beakers at the end of the syringe as shown in Figure 4. A 100 to 200 ml of strip solution passed through the bed of carbon (50 ml at a time) was considered as a sample cycle. The stripped solution (100- 200 ml) was thoroughly mixed and a representative sample taken for gold analysis by ICP-AES. A liter of Zadra strip solution and 0.1/0.2 liters of hot DI-water were passed through each bed of carbon sample to flush out any residual gold under the Zadra elution. The percent gold eluted in the stripping cycle was determined for the process as a measure of its efficiency.

With the Davidson stripping method, the Davidson strip solution was only used for presoaking the carbon samples in the syringe prior to stripping; and the gold cyanide was then flushed out with boiling DI-water. The Davidson strip solution was composed of 10 % KOH, 5 % K_2CO_3 and pH 13. Again a mass of 1 g of each carbon sized fraction

was placed in each syringe fitted with a 0.2/0.45 μm Millipore size membrane filter at its lower end. However, the 2.8 x 1.4 mm and 850 x 425 μm carbon samples were first placed in thimbles that had been trimmed to the 10 ml mark of the syringe to allow for smooth syringe plunger movement in the syringe. The thimbles with the carbon samples were then placed in the syringes, which in turn had fitted at their lower ends 0.2 μm Millipore membrane filters. This was done to ensure that there was enough pressure build-up in the syringe to facilitate the stripping of the carbon samples. Each of the samples was presoaked with 50 ml of the Davidson strip solution at room temperature for 30 minutes in the syringe.

After the presoak time, the strip solution was pumped out into beakers at the lower end of the syringe. This was then followed by pumping 350 ml of boiling DI-water through each sample at an average flow rate of 23 ml/minute. A volume of 400 ml of stripped solution was considered a sample cycle and a total of 1950 ml of hot DI-water and 50 ml of Davidson solution was passed through each sample in its stripping cycle. The average temperatures of the strip solutions measured in the syringes prior to stripping and in the beakers after the stripping process were found to be 85 and 65°C, respectively. The 400 ml of each stripped solution was thoroughly mixed and a sample taken for gold analysis by ICP-AES. The percent gold eluted was determined and the efficiency of the Davidson process was evaluated. The results are presented in Chapter 3. Calculations are shown in the Appendix.

2.3.5 Filter Press Stripping Method

Calgon activated carbon of size fractions as described in the preceding sections and; magnetic AC, BMAC 27B were used for the filter press stripping experiments. The carbons were loaded with gold cyanide for the stripping experiments as described in section 2.3.1; and the set-up for this stripping method is shown in Figure 5. The stripping methods used were the Davidson, Anglo American Research Laboratory (AARL), and Zadra elution methods. The Davidson stripping method was conducted at room temperature (25°C), 60°C and boiling point (98°C) of the strip solution. The AARL elution was carried out at the boiling point of the strip solution, while the Zadra stripping was conducted at room temperature. A 3 g mass of each carbon sample was used for the filter press experiments. The composition and pH of the various strip solutions used were:

- Davidson: 10 % KOH, 5 % K_2CO_3 and pH 13
- AARL: 1 % NaOH, 3 % NaCN and pH 12
- Zadra: 1 % NaOH, 0.5 % NaCN pH 11.5

A pressure of 80 psi was used for stripping all the carbon samples under the different stripping methods. Three grams of each of the carbon samples to be stripped were presoaked for 30 minutes with 100 ml of strip solution in a 1.2L plastic container at room temperature. A liter of stripped solution was considered a sample cycle.

Under the Davidson stripping procedure, after presoaking each AC sample with the Davidson strip solution, tap water at either room temperature, 60°C or boiling point (depending on the elution temperature required) was added to the presoaked carbon sample in the plastic container to the 1-liter mark. This was then immediately poured into the sample chamber of the filter press (as shown in Figure 5), whose bottom part was

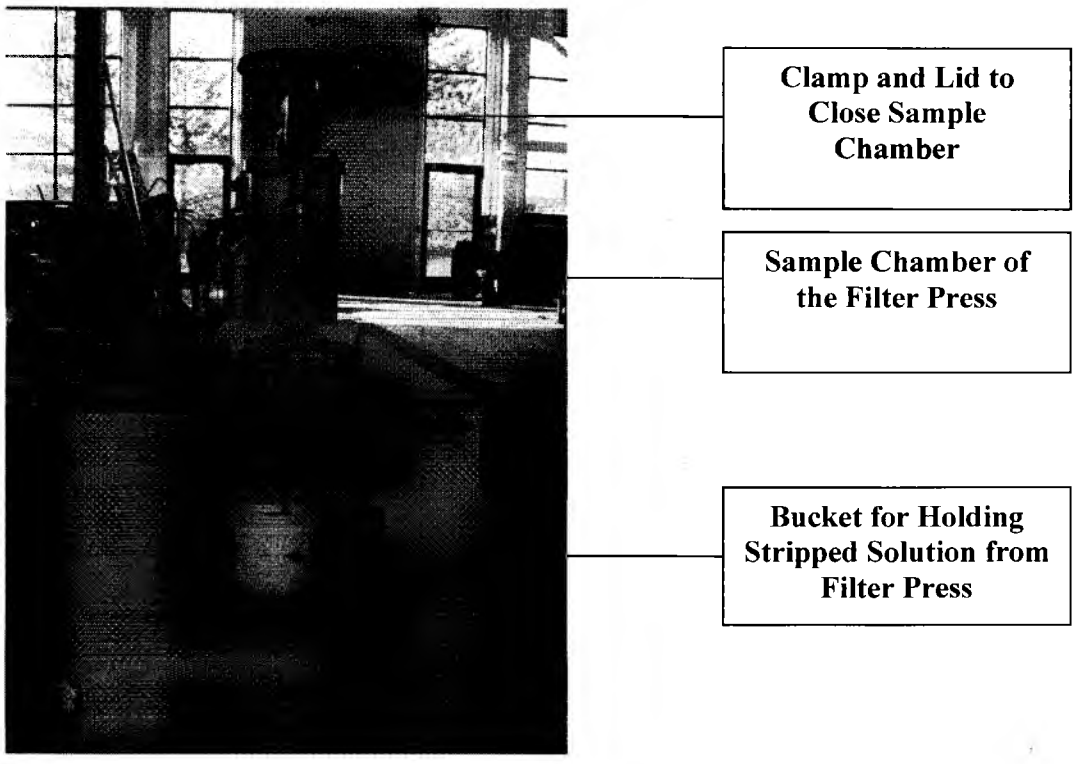


Figure 5 Filter Press Elution Set-up.

lined with both filter cloth and Whatman Cat No 1001 240 filter paper. The sample chamber was closed tightly to prevent strip solution and pressure leaks from the filter press. The pressure which was set at 80 psi was opened and this forced the strip solution through the bed of carbon in the filter press.

The stripped solution was collected in a 5-liter plastic bucket placed at the discharge end of the filter press. The stripped solution collected in the bucket was thoroughly mixed and a sample was stored in sample vials for gold analysis via ICP-AES. The temperature of the strip solution in the sample chamber of the filter press and stripped solution in the bucket at the discharge end of the filter press were measured. For stripping at the boiling point, the average temperature of the strip solution in the sample

chamber of the filter press and the strip solutions in the buckets were 98 and 65°C respectively; and for stripping at 60°C, the corresponding average temperatures measured were 60 and 35°C respectively. A total of 4L of strip solution was passed through each AC sample for stripping at boiling point and room temperature, while a total of 2L of strip solution was passed through the carbon samples stripped at 60°C.

While the same elution procedure was repeated for the AARL and Zadra stripping methods, the AARL stripping was conducted at boiling point and the Zadra elution at room temperature. Results are presented and discussed in Chapter 3. Calculations are shown in the Appendix.

2.4 Carbon (MAC)-in-Leach Experiments with Preg-robbing Ores

Carbon (MAC)-in-leach experiments were conducted to determine the effectiveness of MAC in competing with carbonaceous material in preg-robbing ores for gold recovery. The preg-robbing ore from Newmont's Twin Creek Mine was first prepared prior to the carbon-in –leach experiments.

2.4.1 Ore Preparation

About 1 kg of minus 850 μm preg-robbing ore received from Newmont Mining Corporation was wet-milled in a ceramic ball mill to about 90 % passing 38 μm screen. Lime was added to the ore before the grinding process at 5 g lime/kg ore and the mill feed was 33.3% solids. After 24 hours, grinding at a mill speed of 40 rpm, the contents of the mill were discharged into a 2 liter beaker and 0.5 g of lime sprinkled on the surface of the slurry to help the sedimentation process of this fine-ground material. The beaker with

its contents was allowed to stand overnight under a hood. After the settling process, clear solution at the top of the beaker was decanted and the milled ore was used for the carbon-in-leach experiments.

2.4.2 Carbon (MAC)-in-Leach Experiments

Nine samples (50 g each) of the prepared pre-robbing ore were weighed and placed in 1 liter plastic containers. To each plastic container an appropriate amount of MAC was added. The leach times were 6, 12 and 24 hours; and each leach time period had a set of samples with different weights of MAC added as indicated below:

- 6 hours: 0g MAC, 3g MAC and 6g MAC (at 33.3 % solids for 0 g MAC)
- 12 hours: 0g MAC, 3g MAC and 6g MAC (at 35.0 % solids for 3 g MAC)
- 24 hours: 0g MAC, 3g MAC and 6g MAC (at 36.0 % solids for 6 g MAC)

To the contents of each container, 100 ml of alkaline NaCN leach solution was added. The initial cyanide concentration was 1000 ppm and the leach solution pH was adjusted to pH 11 with NaOH. All the containers containing the samples (9 in number) were loaded into a box in the standing position and the box mounted onto an open-air platform shaker. The leaching process was started with the shaker speed set at 190 rpm and at room temperature. To ensure the presence of oxygen necessary for the leaching process, the containers (reactor vessels) were not covered during the first 2 hours of the leaching process. The vessels were then covered with lids that had nine holes bored into each of them to maintain oxygen presence during the leaching process.

Cyanide concentration during the leaching period was monitored by $AgNO_3$ titration which was conducted at the beginning of the experiment and at end of 6 and 24

hours. In the case of the 6 g MAC sample after 24 hours the cyanide concentration had dropped from 1000 ppm to 637 ppm. After the specified leach time the contents of each reactor were filtered and a sample of the filtrate taken for gold analysis by ICP-AES.

The residue of the carbon samples (3 in number) with the 0 g MAC were allowed to dry at room temperature under a hood while the rest of the carbon residues (6 in number) were washed with tap water back into their respective plastic containers. The pulp of each carbon sample was further diluted with more water to about 5 % solids in their respective containers for separation of the MAC material by a Carpco wet high intensity magnetic separator (WHIMS). In the WHIMS separation process as shown in Figure 6, a peristaltic pump (model number 754912) was used to feed each sample's slurry at 800 ml/minute to the WHIMS separation chamber. The slurry samples fed by the peristaltic pump to the WHIMS separation chamber was also continuously stirred by a stirrer (Masterflex LABO stirrer; model number LR 41D) which was fixed to a medium speed corresponding to a setting 2.5, and was mounted over a 2 L beaker holding the slurry samples been fed. The WHIMS separator was fixed at a low current corresponding to a setting of 1.

A pan was placed at the discharge end of the separation chamber of the WHIMS to collect the nonmagnetic (tails) pulp been discharged. After all the slurry had been fed through the WHIMS, more water was added to the beaker to clean the tubing carrying the slurry samples and any residual nonmagnetic material in the separation chamber of the WHIMS.

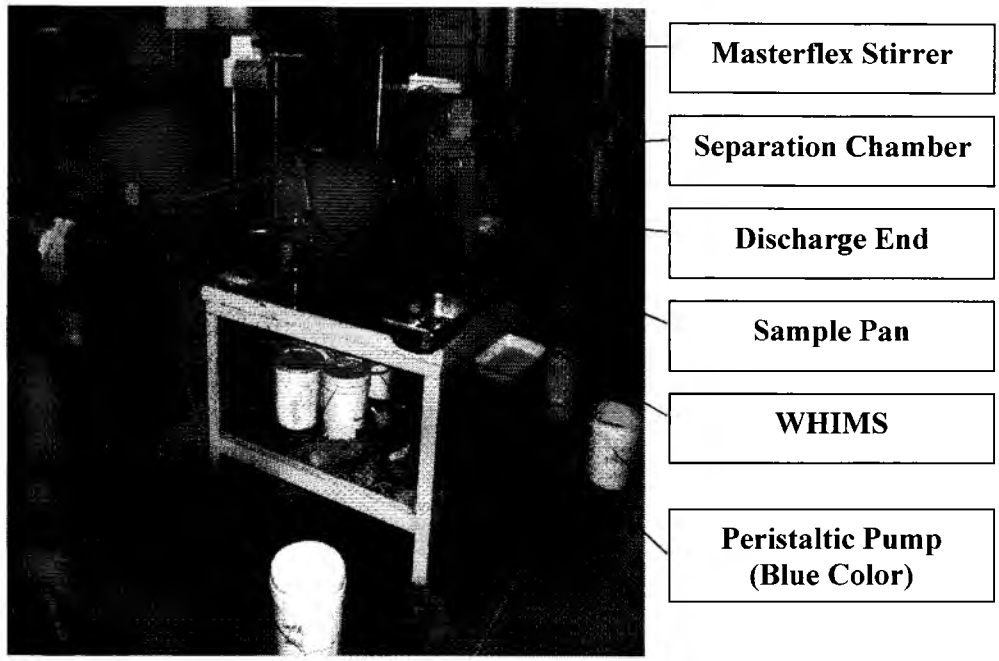


Figure 6 Carpco Wet High Intensity Magnetic Separator.

After the cleaning process the stirrer and peristaltic pump were shut down. The WHIMS magnetic field intensity was then disabled, and the separation chamber removed from the WHIMS and its contents (MAC- the concentrate material and steel balls) were poured into a pan. The steel balls from the separation chamber were then washed thoroughly with water to rid them of any MAC material and reloaded into the chamber. The separation chamber was then put back in the WHIMS and the separation process repeated for the nonmagnetic portion of the sample. This was to ensure that all the MAC material (concentrate) was separated from the nonmagnetic material (tails). The final percentage solids for each slurry sample was estimated to be 2% as more water was added to the sample to obtain an effective separation from the WHIMS.

The magnetic material from the second stage of separation was added to the MAC material from the first stage. Both the concentrate and tails from the WHIMS separation process (shown in Figure 6) were then dewatered by a filter press and then partially dried on a hot plate at low temperature for easy handling. This procedure was repeated for all 6 carbon samples; and a total of 12 dewatered samples (6-tails and 6-concentrates samples) were obtained by the WHIMS separation process. The 12 dewatered samples including the samples with the 0 g MAC (3 in number) and a head feed sample were oven-dried at low temperature overnight in an oven. The dried samples (16 in number) were weighed, bagged, labeled and shipped to Newmont for gold analysis by fire assay. The flowsheet for the preg-robbing experiments is shown in Figure 7. The conspicuous color difference between the magnetic (MAC) and non-magnetic material is shown in Figure 8 after drying. The results and calculations are shown in Chapter 3 and the Appendix, respectively.

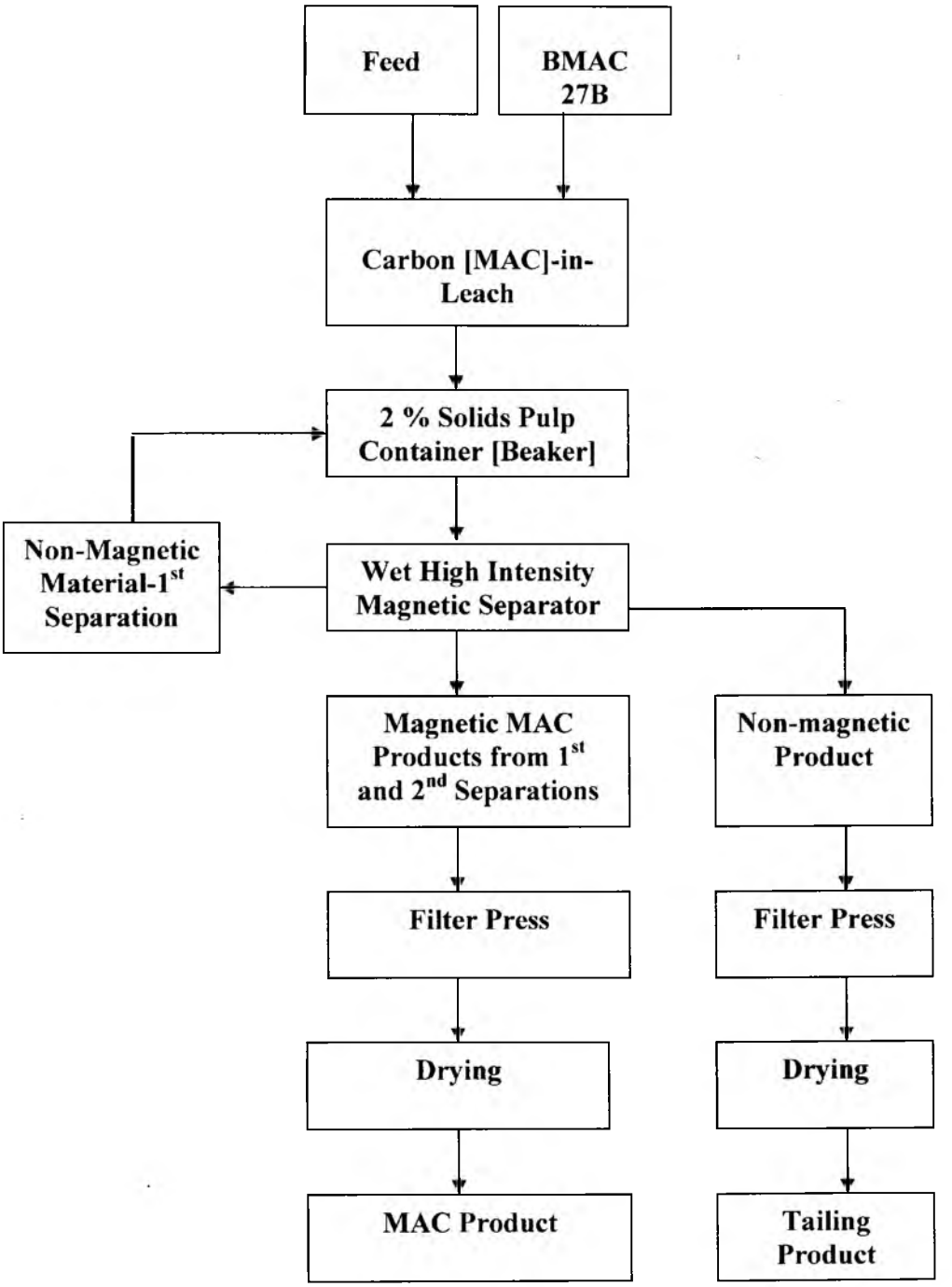


Figure 7 Carbon (MAC)-in-Leach Procedure for Preg-robbing Ore.

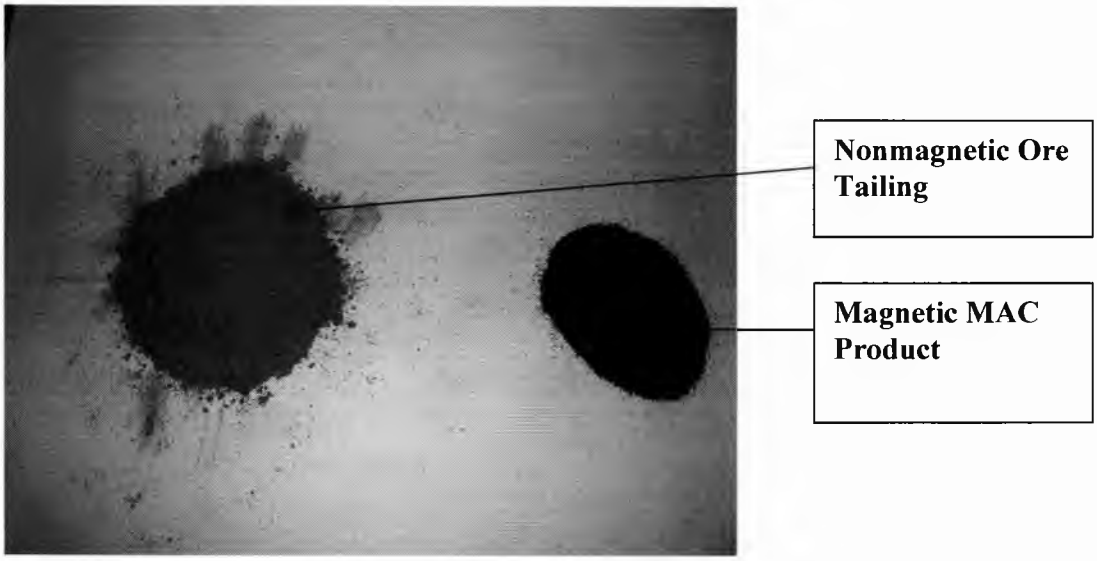


Figure 8 Magnetic and Nonmagnetic Products from WHIMS Separation.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Characterization of AC/MAC

The resistance to attrition and specific surface areas of carbons used were determined and the results are presented in the following sections.

3.1.1 Attrition Resistance Measurements

Attrition resistance (hardness) simply measures the ability of carbon to withstand abrasion/breakage in its applications. For carbon to have a good attrition resistance it must have less than 2% carbon losses in 24-hours of bottle-rolling in the presence of a specified volume of DI-water (40, 41). All the carbon samples used in the research have attrition resistances well below the 2% mark, an indication that the carbons have good attrition resistances. This is particularly true for Barnebey, BMAC 27B and Calgon carbon samples (all supplied by Eriez Magnetics) which had an average percent attrition of 0.29, 0.31 and 0.20 respectively.

The average attrition for the Calgon carbon supplied by Calgon Corporation was 1.08 percent. The average percent difference of the actual mass (mass of carbon on sieve dried after bottle-rolling) and the expected mass (difference between dried undersize of sieve and initial mass of carbon) of the carbons from Eriez Magnetics were 0.10, 0.12 and 0.11; while 0.17 is the average percent difference for the Calgon Corporation carbon.

These results indicate an insignificant variation of the actual mass from the expected mass in the attrition resistance determination process, confirming good attrition resistances of the carbons. The significance of the narrow variation in the attrition resistances of the various carbons indicate that the source material for production of the carbons and the production process were good and efficient.

3.1.2 Specific Surface Area Determination

Granular activated carbons (2.8 x 1.4 mm) have relatively larger particle sizes compared to fine/powdered carbons (850 μm to minus 45μm) and as a result tend to have smaller external surface areas and larger diffusion distances. On the contrary, the fine/powdered carbons exhibit larger external surface areas with smaller diffusion distances (44). The carbons that were evaluated were Calgon AC and magnetic AC, BMAC 27B, (supplied by Eriez Magnetics), and Calgon GRC 22 (supplied by Calgon Corporation, Sri-Lanka origin). The specific surface areas of different particle sizes of Calgon AC and BMAC 27B which were fresh (not loaded with gold cyanide), loaded (loaded with gold cyanide), and stripped (gold cyanide removed) were determined by the BET method and the results are presented in Table 3.

There are no significant differences in the specific surface areas of the different particle sizes of fresh, loaded and stripped Calgon AC and BMAC 27B. What is clear from Table 3 is the fact that the fresh and stripped carbons have comparatively larger specific surface areas than the loaded carbons, which is to be expected as this highlights the concept behind carbon regeneration; to open up blocked pores of activated carbons in the carbon adsorption-desorption process. It must be pointed out that the single point

Table 3
Specific Surface Area Measurements of Calgon Activated Carbon and BMAC 27B (Source: Eriez Magnetics) by BET.

Carbon type and particle size	Surface area [m^2/g]		
	Fresh carbon	**Loaded carbon**	**Stripped carbon**
BMAC 27B [191x49µm]	1736	1012	1146
Calgon AC [2.80x1.40mm]	1326	918	1031
Calgon AC [850x425µm]	1249	998	1112
Calgon AC [212x45µm]	1245	1047	1155
Calgon AC [minus 45µm]	1095	917	1018

evaluation of the data was used in view of the fact that it has less than 5 percent error. In this case, only the first point on the BET isotherm was selected.

The specific surface areas of sized particles of Calgon GRC 22 and BMAC 27B were also determined by the BET method and the results are presented in Table 4. Again the results indicate no significant differences in the specific surface areas of the carbons. In Table 5, the specific surface areas of the fresh Calgon carbon supplied by Eriez Magnetics and Calgon GRC 22, supplied by Calgon Corporation have been compared in terms of percent difference. It is clear from Table 5 that, there is good agreement in the results for the fresh Calgon carbon in Table 3 and Calgon GRC 22 in Table 4, given the fact that the percentage difference in surface area is between 1 and 6%. The large percent difference in the BMAC 27B readings may be a result of experimental error.

3.2 Adsorption Capacity

It should be noted that micropore volume is a structural parameter of great importance to the adsorption of gold, because the micropores provide adsorption sites that can wrap around the adsorbate (6). Gold adsorption capacity (K-value) gives the gold loading on the carbon in equilibrium with 1 ppm gold solution after 24 hours contact time; and for effective activated carbon samples the K-value should be greater than 25 kg Au/t C (40, 41).

Though the exact mechanism of the adsorption of gold (in the form of aurocyanide) onto AC has generated controversies, significant progress has been made to show how gold is thought to be adsorbed by carbon. Gold in the form of the aurocyanide

Table 4
Specific Surface Area Measurements of Fresh Calgon Carbon GRC 22 (Source: Calgon Corporation) and BMAC 27B (Source: Eriez Magnetics) by BET.

Carbon type and particle size	Surface area [m^2/g]
BMAC 27B [191 x 49 μm]	1092
Calgon GRC 22 [2.80 x 1.40mm]	1308
Calgon GRC 22 [850 x 425 μm]	1167
Calgon GRC 22 [425 x 212 μm]	1167
Calgon GRC 22 [212 x 45 μm]	1059

Table 5
Percent Difference in Specific Surface Area Measurements of Calgon Carbon GRC 22 (Calgon Corporation), and Calgon Carbon and BMAC 27B (Eriez Magnetics) by BET.

Carbon type and particle size	Surface area [m^2/g]		Percent difference
BMAC 27B [191 x 49 μm]	1736	1092	37.1
	Calgon AC	**Calgon GRC 22 AC**	
2.80 x1.40 mm	1326	1308	1.3
850 x 425 μm	1249	1167	6.6
212 x 45 μm	1245	1167	6.3

anion is thought to be adsorbed through an ion-pair mechanism, in which the ion-pairs $\{M^{n+}[Au(CN)_2^-]_n\}$ are adsorbed at the carbon surface without chemical change (6). Work done at the University of Utah's Department of Metallurgical Engineering by Sibrell suggests that the adsorption of gold by AC is site-specific in nature, and that the most favored sites are sites with defects (34). The adsorption capacity values presented in Tables 6 to 8 are all greater than the expected minimum value, an indication that the activated carbons studied have good loading capacities. The adsorption isotherms are reported in the Appendix.

Table 6
Adsorption Capacity Values for Calgon AC and BMAC 27B Carbon (Eriez Magnetics).

Particle size	Adsorption capacity [K-value; kg Au/t C]
Calgon AC 2.80 x 1.4 mm	28.87
Calgon AC 850 x 425 µm	29.36
Calgon AC 212 x 45 µm	32.68
Calgon AC 45 x 25 µm	32.06
BMAC 27B [191 x 49µm]	31.18

Carbon samples of different weights were loaded with 114.12 mg Au/L solution at pH = 10.41, 25°C, rpm = 200 for 24 hours.

Table 7
Adsorption Capacity Values for Calgon GRC 22 and BMAC 27B Carbons.

Particle size	Adsorption capacity [K-value; kg Au/t C]
Calgon GRC 22 [2 80 x 1.4 mm]	28.45
Calgon GRC 22 [850 x 425 µm]	29.14
Calgon GRC 22 [425 x 212 µm]	30.00
Calgon GRC 22 [212 x 45 µm]	33.46
BMAC 27B [191 x 49µm]	34.80

Carbon samples of different weights were loaded with 98.63 mg Au/L solution at pH = 10.10, 25°C, rpm = 200 for 24 hours.

Table 8
Adsorption Capacity Values for Newmont's Barnebey Carbon.

Particle size	Adsorption capacity [K-value; kg Au/t C]
Barnebey [2.80 x 1.4 mm]	30.20
Barnebey [212 x 45 μm]	38.60
BMAC 27B [191 x 49μm]	32.30

Carbon samples of different weights were loaded with 105.35 mg Au/L solution at pH = 11.20, 25°C, rpm = 200 for 24 hours.

Another observation clearly seen in Tables 6 to 8 is the fact that K-value increases as activated carbon particles decrease; this observation is consistent with the work of Munoz at the Department of Metallurgical Engineering, University of Utah (28). According to Miller et al., even though gold adsorption varies widely on a weight basis, adsorption densities are much more uniform (45). They demonstrated that the space occupied [packing area] on the surface of the carbon by the adsorbed gold cyanide complex, calculated from adsorption densities data is about 500Å^2 per gold complex.

These results suggest that less than 1% of the AC surface area is occupied by the gold cyanide ion pair. Another point worth noting in the adsorption capacity results is the fact that the ultimate equilibrium gold loading capacity of the AC's is not influenced by the size of its particles (22, 46).The notion that the ultimate loading capacity of AC is independent of particle size is further substantiated by the results of section 3.4, for the carbon adsorption-desorption experiments described in Chapter 2.The results show

instances of significant variations in carbon loadings; however, these differences are random and can be attributed to experimental error.

In summary, it can be concluded that the AC's and the magnetic AC, BMAC 27B used in this research have good loading capacities.

3.2.1 Fire Assay

Fire assay was used as a control measure to verify that results obtained by ICP-AES analytical procedures were reasonable. For example, data obtained by ICP-AES were cross-checked with fire assay data for some samples. Samples were taken from the carbon adsorption and elution process for fire assaying; and these results were then compared with ICP-AES data to find out whether the ICP-AES results were reasonable within the margin of experimental error. Samples of loaded and stripped carbons were sent to Newmont Metallurgical Laboratory for fire assaying and the ICP-AES readings were taken at the Department of Metallurgical Engineering, University of Utah. The results obtained from both the fire assay and ICP-AES analyses are compared as shown in Tables 9 to 11.

Tables 9 and 11 depict gold- loaded Calgon and magnetic AC's while Table 10 shows the stripped Calgon AC of Table 9. The results clearly show that the ICP-AES results are higher (varying from 11 to 50%) than the fire assay results in all instances except for only two places in Table 10. The anomaly in Table 10 is seen in the 212 x 45 μm Calgon carbon where the fire assay result is 22.45% greater than the ICP-AES result.

Table 9
Calgon Carbon 9 (Source: Eriez Magnetics); ICP-AES and Fire Assay Results of Loaded Activated Carbons Compared.

Particle size	ICP results [kg Au/t C]	Fire assay results [kg Au/t C]	Percent difference
2.8 x 1.4 mm	44.81	38.70	13.64
850 x 425µm	47.07	37.0	21.39
212 x 45µm	47.59	38.90	18.60
Minus 45µm	45.27	36.6	19.15

Table 10
Calgon Carbon (Source: Eriez Magnetics); ICP-AES and Fire Assay Results of Stripped Activated Carbons Compared.

Particle size	ICP results [kg Au/t C]	Fire assay results [kg Au/t C]	Percent difference
2.8 x 1.4 mm	16.3	8.2	49.69
850 x 425µm	28.3	16.3	42.40
212 x 45µm	24.5	30.0	-22.45
Minus 45µm	23.2	22.9	1.29

Table 11
Calgon Carbon GRC 22 (Calgon Corporation) and BMAC 27B (Source: Eriez Magnetics); ICP-AES and Fire Assay Results of Loaded Activated Carbons Compared.

Particle size	ICP results [kg Au/t C]	Fire assay results [kg Au/t C]	Percent difference
2.8 x 1.4 mm	75.02	61.85	17.56
850 x 425µm	78.28	63.93	18.33
212 x 45µm	79.71	67.35	15.51
Minus 45µm	72.05	60.85	15.54
BMAC 27B [191 x 49µm]	77.45	69.06	10.83

Also for the minus 45 µm sample, the ICP-AES result is only 1.29% greater than the fire result. Assigning reasons for the anomaly in Table 10 and the deviations of the fire assay results from those of the ICP-AES would be speculation as no repeat tests were conducted to verify the causes of the anomaly and deviations due to a lack of samples. In spite of the anomalies in Table 10 and the deviations of the fire assay results from those the ICP-AES, the fire assay control technique was useful in allowing the effectiveness of

the loading and stripping of the carbons to be verified; and as a result more effective stripping methods were developed to help the research effort.

3.2.2 Scanning Electron Microscopy (SEM)

SEM images of fresh, loaded and stripped AC samples were taken to help gain an understanding of their surface structural properties when they were not loaded with gold cyanide, then loaded with gold cyanide and stripped of gold cyanide. Backscattered electron images were also taken of the loaded carbon samples at the Newmont Metallurgical Laboratory for the same purpose. The SEM images taken of the different size fractions of fresh, loaded and stripped Calgon and magnetic activated carbons are presented in Figures 9 and 10; while backscattered electron micrographs for loaded Calgon and magnetic activated carbons are shown in Figure 11. The SEM images taken at 50X magnification and a scale of 200 μm do not present clear structural differences between the fresh, loaded, stripped Calgon and magnetic activated carbons.

On the contrary, the backscattered micrographs in Figure 11 show distinctive differences. For example, the light grey and grey colored particles [or patches] in the micrographs indicate the presence of high gold content. This is to be expected as the carbons were loaded with a high gold content for this analysis as already presented in Table 11, which compares fire assay and ICP data. It can be seen from Table 11 that both the fire assay and ICP results indicate high gold loadings for all the carbon samples.

The bright specks as seen in the 212 x 45 microns and BMAC 28B micrographs are indicative of the presence of iron. The presence of iron in the 212 x 45 microns carbon sample could have come from steel balls used in grinding the carbon, and the fact

BMAC 27B (191 x 49 µm): Fresh

BMAC 27B (191 x 49 µm): Loaded

BMAC 27B (191 x 49 µm): Stripped

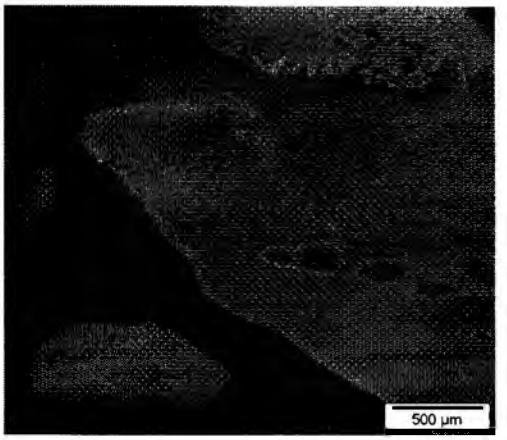
Figure 9 SEM Images of Fresh, Loaded and Stripped BMAC 27B (191 x 49 µm).

Calgon AC (2.80 x1.40 mm): Fresh

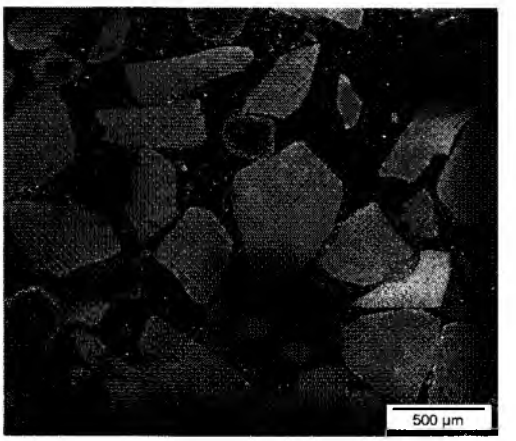
Calgon AC (2.80 x1.40 mm): Loaded

Calgon AC (2.80 x 1.40 mm): Stripped

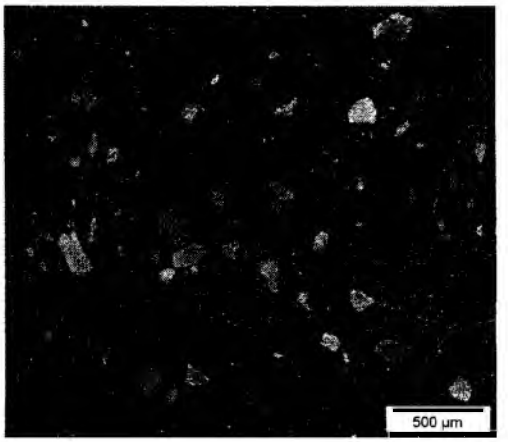
Figure 10 Images of Fresh, Loaded and Stripped Calgon Carbon (2.8 x 1.4 mm).



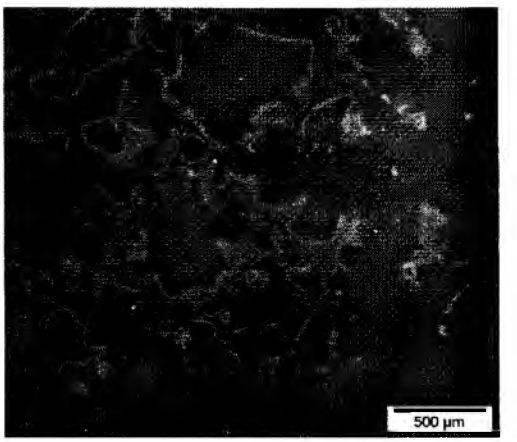
Calgon AC (2.8 x 1.4 mm)



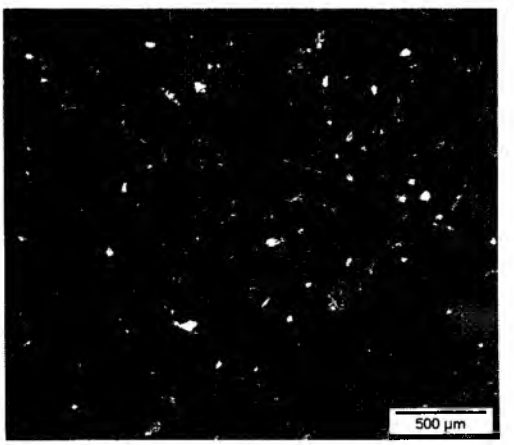
Calgon AC (850 x 425 µm)



Calgon AC (212 x 45 µm)



Calgon AC (minus 45 µm)



BMAC 27B (191 x 49 µm)

Figure 11 Backscattered Electron Images of Magnetic AC and Calgon AC.

that it was ground a little longer than the other size fractions probably exposed it to the iron. However, the presence of iron in the MAC is not unusual as iron is used as a precursor in its production.

3.3 Adsorption Rate

The rate of adsorption for AC particles of different size was determined. The AC samples used included Barnebey (Newmont Mining), Calgon and Magnetic AC, BMAC 27B (Eriez Magnetics), and Calgon GRC 22 (Calgon Corporation). The purpose of the rate experiments was to study the effect that AC particle size has on the rate of adsorption. In addition, the rate study was done to evaluate the adsorptive capability of Magnetic AC, BMAC 27B as compared to AC; that is, whether BMAC 27B has an adsorption rate comparable with traditional activated carbons. Usually, for activated carbons to be considered as having an effective rate of adsorption, the percentage gold adsorbed by 1g of carbon from 10 mg/L gold solution in 1 hour should be greater than 60% (40, 41).

The results from the rate of adsorption experiments for the four types of AC used are shown in Figures 12 to 16 and Table 12. Figures 12 to 15 present results for rate of gold adsorption while Figure 16 shows the relationship between initial rate of gold adsorption and activated carbon particle size. Table 12 depicts the first order reaction velocity constants calculated from the initial rates of gold adsorption. It is evident from the results presented that rate of adsorption increases as the particle size decreases. In particular, Figures 14 and 15 clearly reveal this trend; as the AC decreases in size from 2.8 x 1.4 mm to 212 x 45 μm and minus 45 μm, the rate of adsorption increases quite

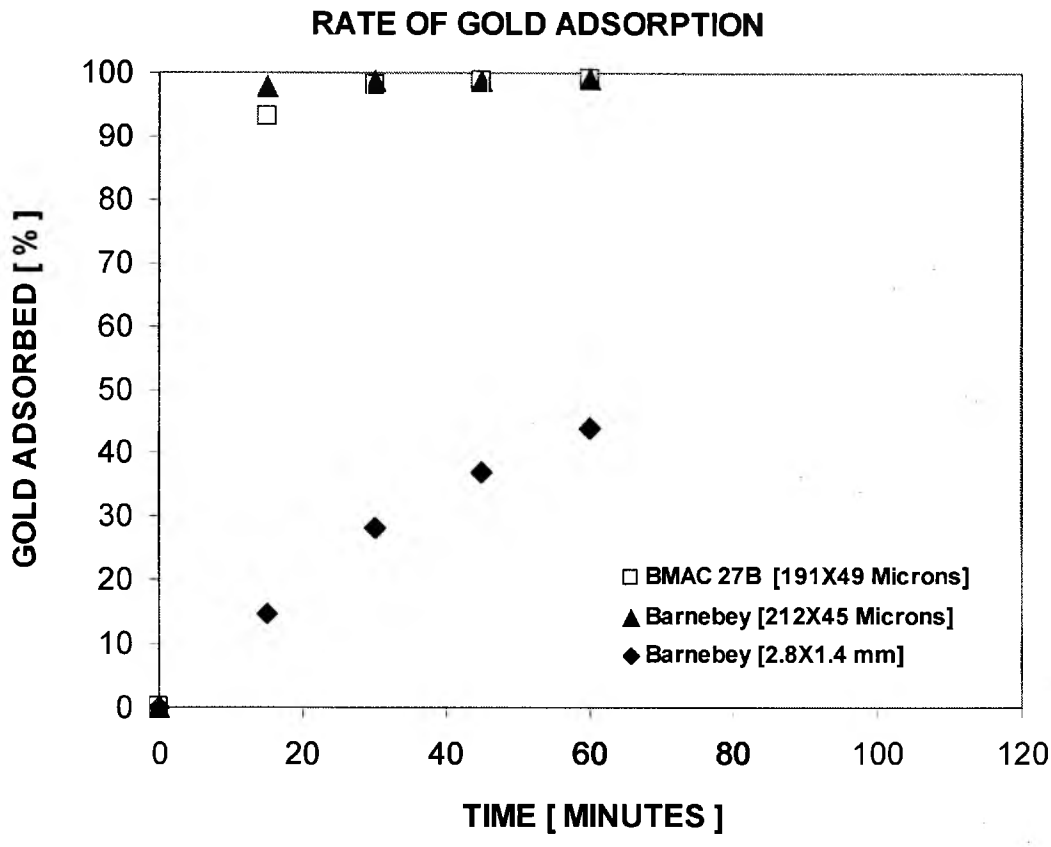


Figure 12 Rate of Adsorption for Barnebey (Newmont Corporation) and BMAC 27B Carbons (Eriez Magnetics).
Loading conditions: 1 g carbon in 1L of 10 mg/L Au solution @ 25°C, pH of 11 and a shaker rpm of 180 for 60 minutes.

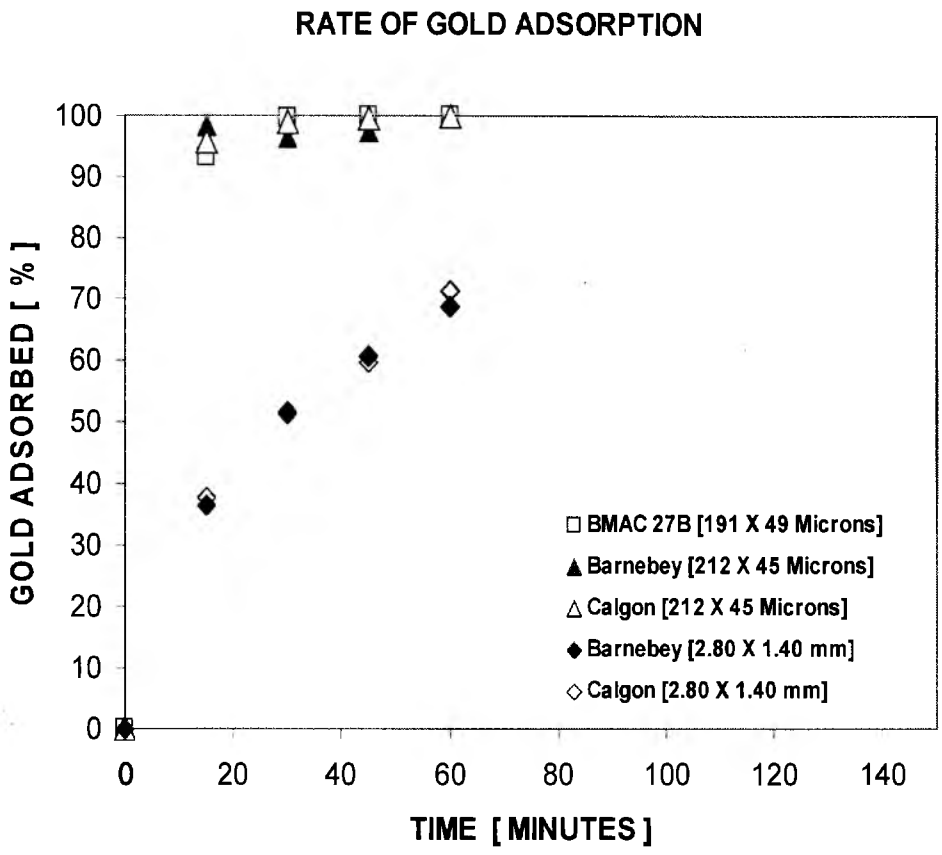


Figure 13 Rate of Adsorption for Different Activated Carbons.
Carbon type: Barnebey (Newmont Corporation); BMAC 27B and Calgon (Eriez Magnetics).Loading conditions: 1 g carbon in 1L of 10 mg/L Au solution @ 25°C, pH of 11.20 and a shaker rpm of 180 for 60 minutes.

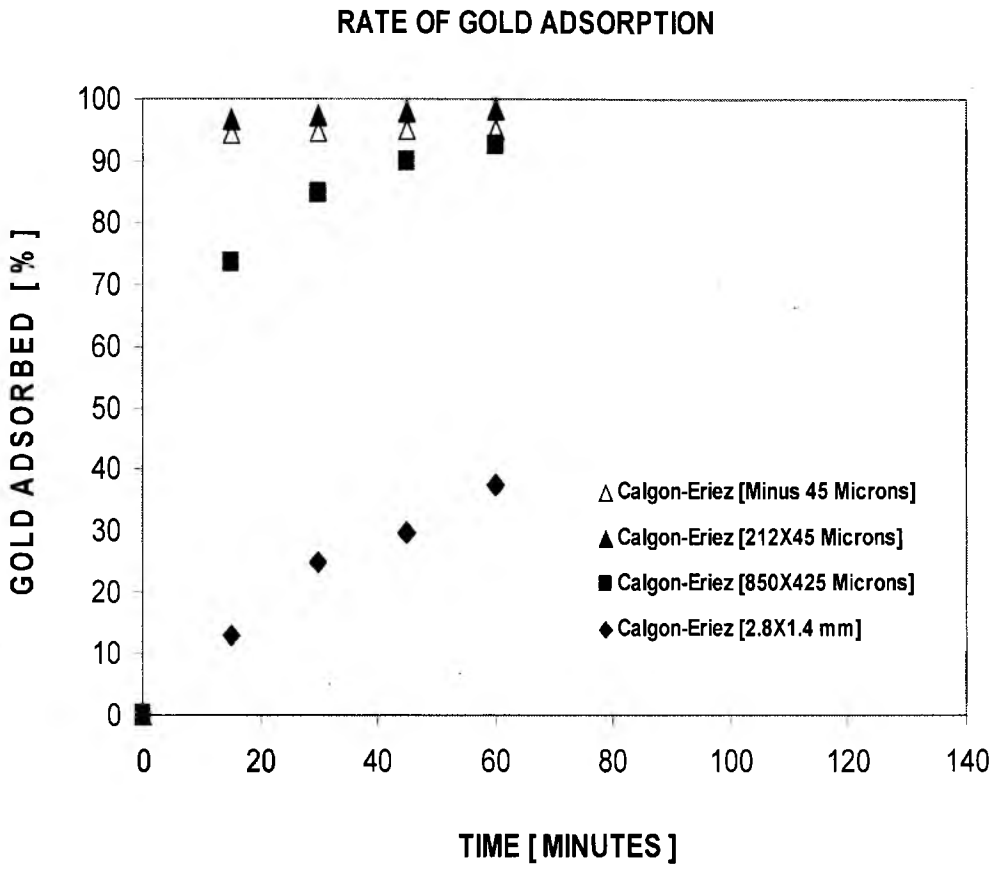


Figure 14 Rate of Adsorption for Calgon Activated Carbon (Eriez Magnetics). Loading conditions: 1 g carbon in 1L of 10 mg/L Au solution @ 25°C, pH of 10.56 and shaker rpm of 180 for 60 minutes.

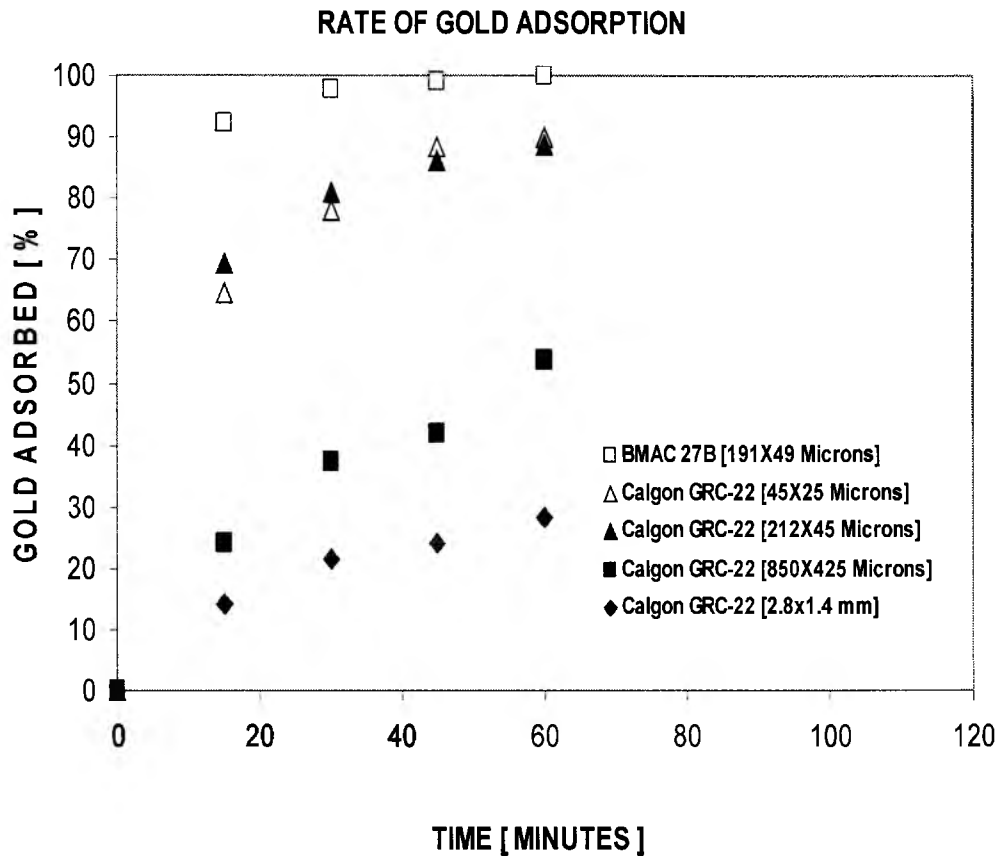


Figure 15 Rate of Adsorption for Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons.
Loading conditions: 1 g carbon in 1L of 10 mg/L Au solution @ 25°C, pH of 10.56 and shaker rpm of 180 for 60 minutes.

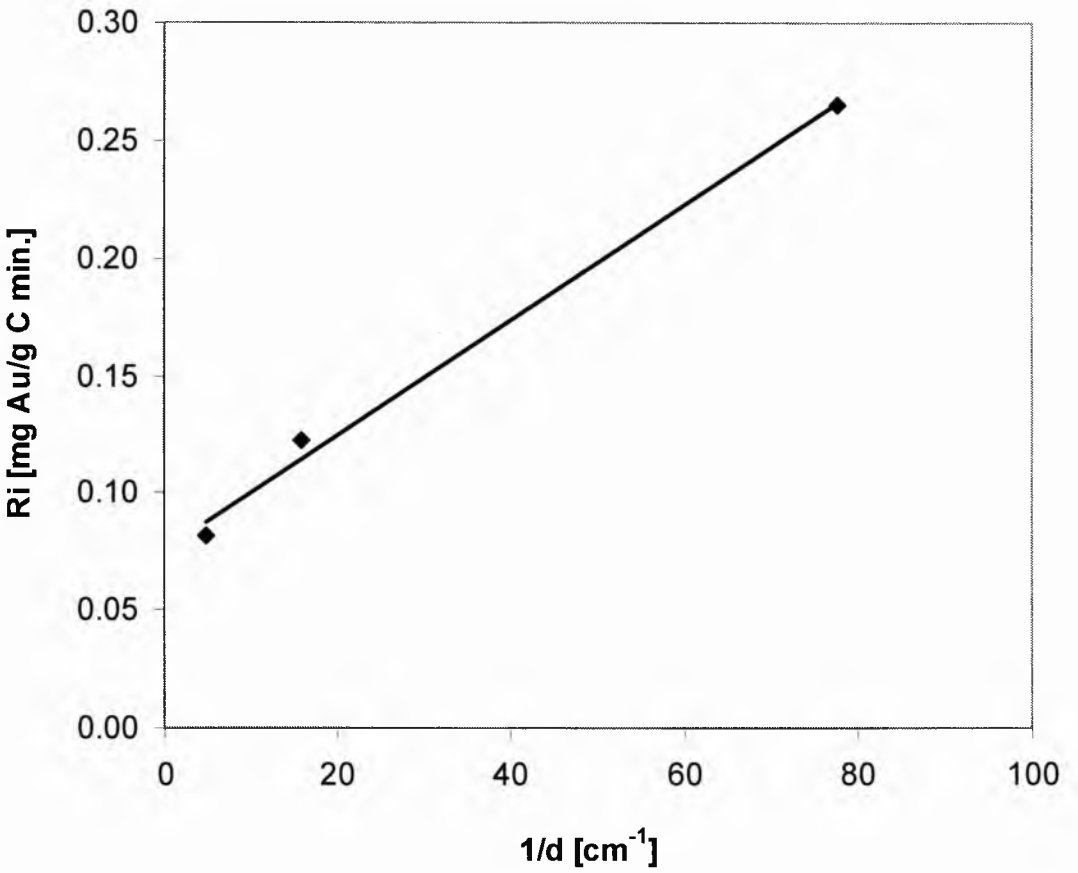


Figure 16 Relationship Between Initial Rate of Gold Adsorption and Activated Carbon Particle Size.

Table 12
First Order Reaction Velocity Constants Calculated from Initial Rates of Adsorption

Carbon type	Reaction velocity constants [cm/s]						
	2.8x1.4 mm	850x425 µm	425x212 µm	212x45 µm	191x49 µm	45x25 µm	Minus 45 µm
Calgon	2.39E-03			4.95E-04			1.90E-
Eriez	1.77E-03			4.87E-04			04
Calgon		4.83E-04	2.39E-03			4.95E-	
GRC-22	2.15E-03					04	
Barneby	2.29E-03			4.94E-04			
	2.15E-03			4.83E-04			
BMAC					4.58E-04		
27B					4.65E-04		
					4.56E-04		

significantly. The results also show that while the finer carbons adsorbed 70% of the gold in the first 15 minutes and nearly 100% after 1 hour, the coarser carbons, GAC, was consistently below 20% in the first 15 minutes and also below 40% after 1 hour.

As expected the rate of gold cyanide adsorption increases with a decrease in carbon particle size. This notion is reinforced by Figure 16, which clearly shows the relationship between initial rate of gold adsorption and the average diameters of activated carbon particles used in the research. The inverse dependence of rate on carbon particle size is clearly seen in the linear relationship between initial rate and the inverse of carbon particle diameter plot. In Figure 16, three size fractions of carbon particles (2.8 x 1.4 mm, 850 x 425 µm and 212 x 45 µm) whose initial rates could be determined were used for the plot.

The initial rate of gold adsorption (Ri) was determined from the slope of a plot of amount of gold on carbon (mg Au/g C) against time (minutes). The reaction velocity constant (k) values, as shown in Table 12, were then determined from the initial rates using equation 5, and the surface area (A in equation 5) of the carbon particles was determined from the geometric mean diameters of the carbon particles using equation 6.

$$k = R_i / [A \times C_i \times 60] \quad (5)$$

where:

k = Reaction velocity. Constant (cm/s)

R_i = Initial rate of Au adsorption (mg Au/g C min.)

A = Specific surface area of carbon particles (cm^2/g)

C_i = Initial Au concentration in solution (mg/cm^3)

60 = Conversion factor (s/min.)

The specific surface area of the carbon particles were then obtained from equation 6:

$$A = 6 / [\rho \times d] \quad (6)$$

where:

ρ = Density of carbon (g/cm^3)

d = Geometric mean diameter of the sized fractions of carbon particles

Given that:

The density of carbon (g/cm^{-3}) = 0.42

Conversion factor = 6

It is worth pointing out that the results are in agreement with the work done by Munoz at the University of Utah's Department of Metallurgical Engineering (28) and is also consistent with what has been reported in the literature (22, 46).

The magnetic activated carbon, BMAC 27B, as Figures 12, 13 and 15 reveal has an excellent rate of adsorption; attaining an average adsorption rate of 90% in the first 15 minutes and nearly 100% after 1 hour. Its adsorptive capability is comparable only to the finest AC sample, which is the 212 x 45 μm particle size fraction. The fast rate of adsorption exhibited by BMAC 27B makes it a good adsorbent with the potential to replace GAC, especially for the treatment of preg-robbing gold ores.

Mathematical modeling of the effect of activated carbon particle size on the rate of gold adsorption is beyond the scope of this thesis; however, it will suffice to mention the ideas behind the kinetic models proposed by some researchers. Cho et al. (47) proposed that gold adsorption by activated carbon is controlled by pore diffusion, and the aurodicyanide adsorption occurs on the active sites. Consequently, when the rate of adsorption is faster than the diffusion process, local equilibrium between the AC surface and gold aurodicyanide can be assumed.

Fuerstenau et al. (48) proposed a three stage adsorption reaction process in the development of their model. They argued that the first stage of the adsorption process is rapid and controlled by diffusion of the aurodicyanide complex onto external surface sites of the activated carbon particles. The intermediate and final stages of the adsorption process, however, are much slower and diffusion of the aurodicyanide complex through the pores (the macropores are filled first, followed by the mesopores and micropores) in

the activated carbon becomes rate controlling. The kinetic model proposed by Le Roux et al. (49) assumes adsorption in batch systems, where it is assumed that the rate of adsorbate removal from solution can be described by initial film transfer dominance followed by intraparticle diffusion. Intraparticle diffusion combines pore diffusion (diffusion through the fluids inside the pores) and surface diffusion (migration of the adsorbed molecules along the internal pore walls). Finally, Van Deventer (50) proposed a dual-rate model which was meant to explain why equilibrium is usually approached slowly in the adsorption of the aurodicyanide complex by activated carbons.

The trend in the rate of gold adsorption results presented suggests that the rate of gold adsorption is inversely proportional to the AC particle size. The first order reaction velocity constant values presented in Table 12 are independent of the activated carbon particle size and the concentration of the gold cyanide solution. The values are consistent with what has been reported in the literature (49, 51), and further supports the notion that initial rate of gold adsorption may be controlled by film diffusion through mass transfer boundary layer (52) or by surface reaction (53).

In summary, it has been substantiated that the rate of gold cyanide adsorption has an inverse dependence on the AC particles size. In addition, the fast rate of adsorption by the BMAC 27B sample makes it an excellent adsorbent for the recovery of gold from alkaline cyanide solutions, and especially for the processing of preg-robbing ores.

3.4 Elution Rate

Significant progress has been made in understanding the nature of gold adsorption from alkaline solutions by activated carbons; in particular its adsorption rate and

capacity; however, the amount of research devoted to the fundamental study of elution is rather limited; with the nature of the stripping reaction not very well understood. In particular, the effect that activated carbon particle size has on the stripping of adsorbed gold cyanide is not well documented in the literature. However, it is well known in the gold industry that substantial gold losses on fine carbons decrease the recovery. As a result high granular activated carbon inventories have to be maintained to accommodate carbons losses due to attrition and abrasion of carbon-on-carbon and carbon-on-screen.

The purpose of the elution experiments was to evaluate the influence of particle size, temperature, pressure and strip solution composition on the stripping of adsorbed gold cyanide from activated carbons. The four stripping methods employed were the atmospheric Zadra, syringe and hydraulic press, syringe pump and filter press elution methods. The general understanding is that the factors that inhibit the adsorption of gold cyanide on activated carbon will favor the stripping reaction (6, 22). It is the expectation that the finer carbon particles, temperature of the strip solution, pressure and the strip solution composition will favor the stripping reaction. In particular, it is expected that the stripping reaction will be faster for the finer activated carbons than for the GAC since the finer carbons have relatively larger external surface areas in contact with the strip solution compared with the GAC. The results from the elution experiments described in Chapter 2 are presented and discussed in the following sections.

3.4.1 Atmospheric Zadra Elution

The atmospheric Zadra elution experiments were conducted at atmospheric pressure and elevated temperatures (98-100^{o}C) of the Zadra strip solution. As has already

been stated in Chapter 2, this method of stripping was studied under batch mode without solution replacement (or batch-continuous stripping) and with incremental solution replacement. In other words, for the batch-continuous stripping method, a specified volume of strip solution was used for stripping each size fraction of carbon sample in the sample's stripping cycle without replacement of the strip solution. While in the batch with solution replacement method, the strip solution was replaced with fresh strip solution after each sample cycle, that is, the strip solution was poured out of the three-neck flask and replaced with fresh strip solution.

In one of the batch-continuous elution experiments, the strip solution concentration was adjusted prior to stripping to facilitate the evaluation of the effect of back reaction on the elution process. Furthermore, in the batch-continuous stripping mode air was continuously bubbled into the elution reaction chamber to investigate whether gold cyanide was adsorbed on the AC in the reduced (metallic) form. Stripping time was varied from 1 to 30 hours in some cases.

The results are presented in Figures 17 to 24. The stripping conditions used for the experiments are given in the figure captions, that is, the loading of gold cyanide on each AC size fraction and the specific stripping conditions for each experiment are specified. The stripping conditions that were not changed under this stripping method were temperature and pressure. Figures 17 to 22 are the results for batch-continuous stripping (batch stripping without solution replacement) while Figures 23 to 24 are for batch stripping with incremental solution replacement. The results indicate that the stripping reaction favors the coarser carbon particles, that is, the coarser the carbon

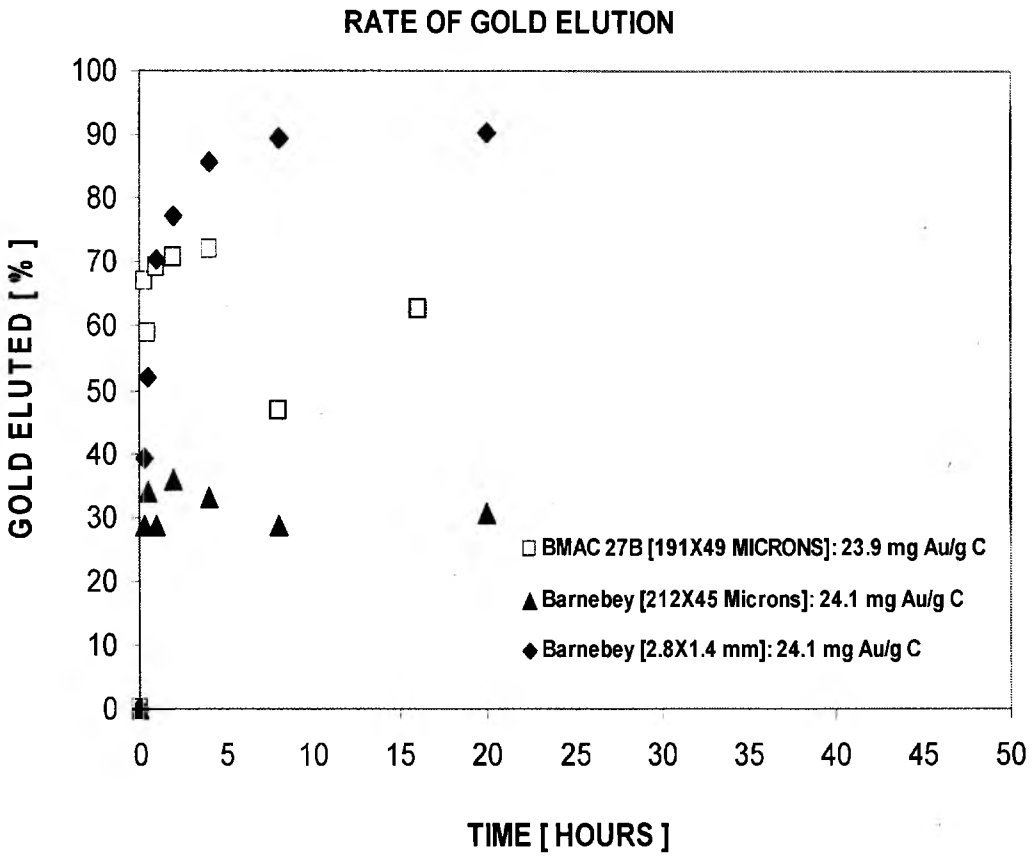


Figure 17 Rate of Elution of BMAC 27B and Barnebey Carbons by Atmospheric Zadra Elution for 20 Hours.
Loading conditions: 10 g carbon in 1L of 250 mg/L Au solution @ 25°C, pH of 10.63 and a shaker rpm of 180 for 24 hours. Elution conditions: Presoaked for 15 minutes; 0.5% NaCN and 1% NaOH in 1L @ pH of 12.7 and 98°C.

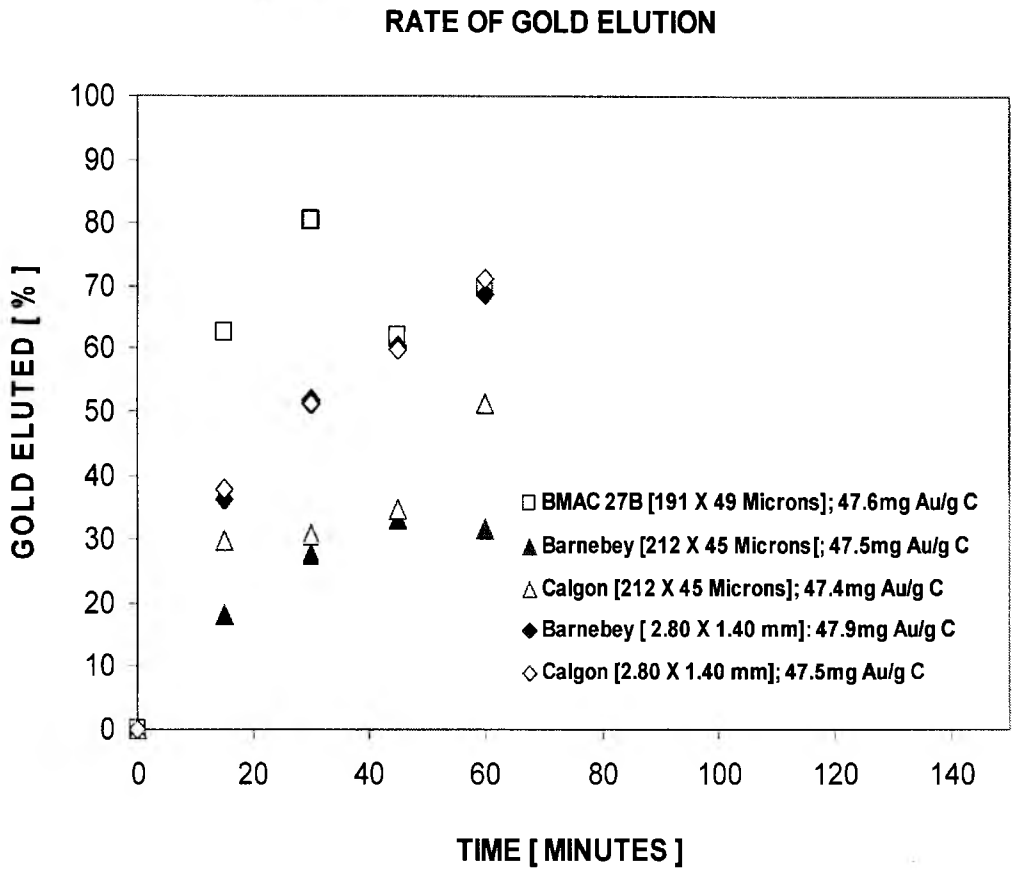


Figure 18 Rate of Elution of Different Activated Carbons by Atmospheric Zadra Elution.Carbon type: Barnebey (Newmont Corporation); BMAC 27B and Calgon (Eriez Magnetics).
Loading conditions: 1 g carbon in 0.2L of 250 mg/L Au solution @ 25°C, pH of 10.50 and a shaker rpm of 200 for 24 hours. Elution conditions: 0.5% NaCN and 1% NaOH in 0.2L @ pH of 12.9 and 98°C.

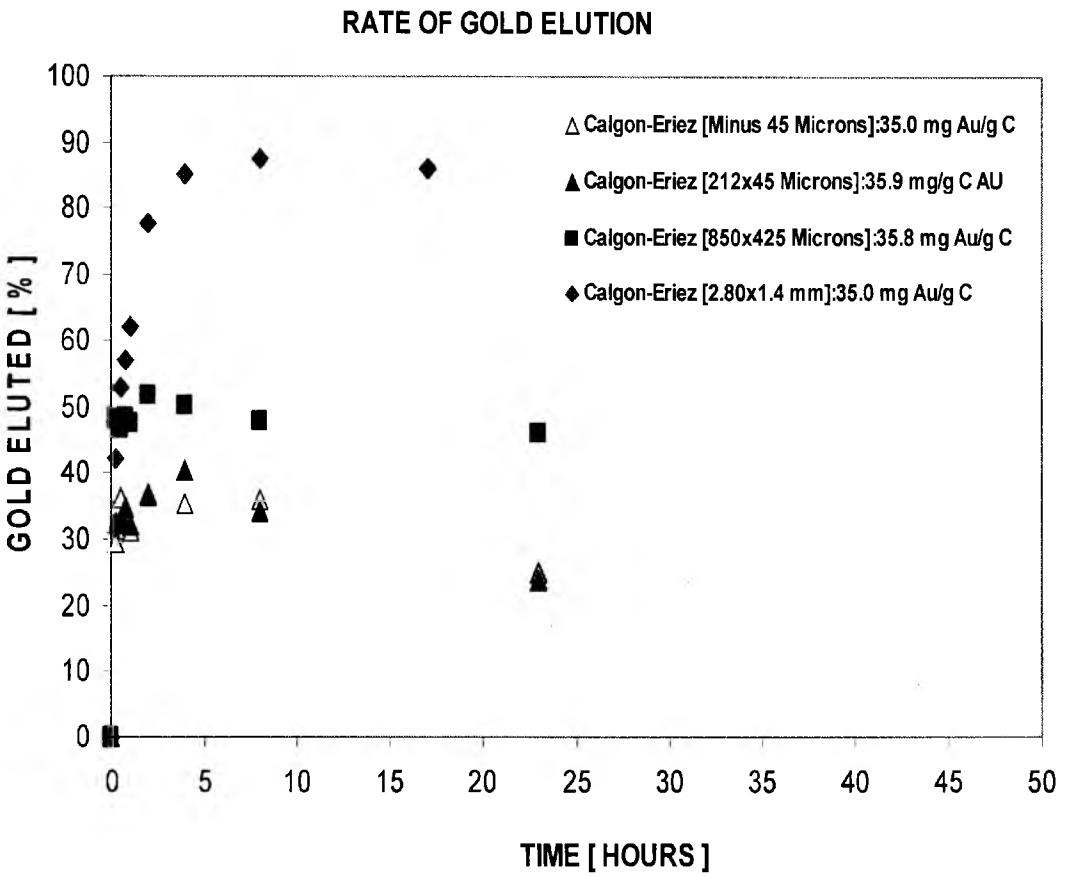


Figure 19 Rate of Elution of Calgon Activated Carbon (Eriez Magnetics) by Atmospheric Zadra Elution for 23 Hours.
Loading conditions: 5 g carbon in 1L of 250 mg/L Au solution @ 25°C, pH of 10 and a shaker rpm of 180 for 24 hours. Elution conditions: 0.5% NaCN and 1% NaOH in 0.5L @ pH of 12.91 and 98°C.

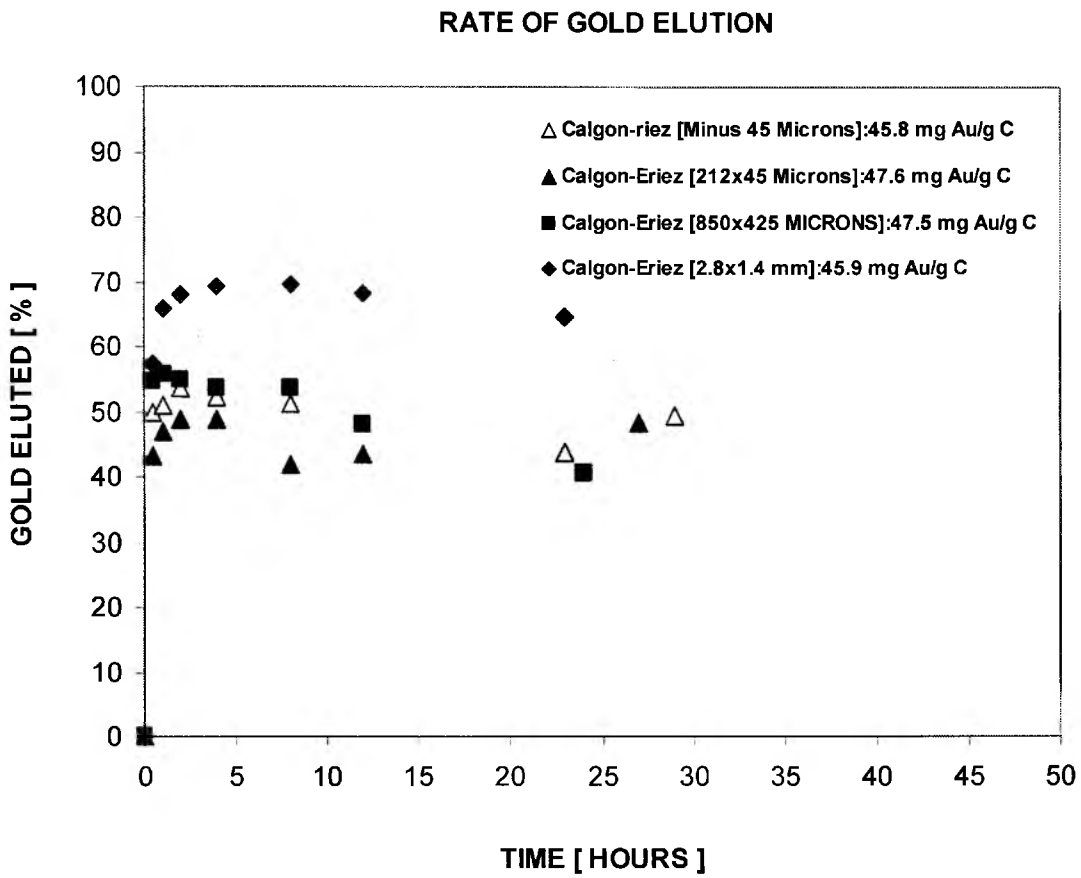


Figure 20 Rate of Elution of Calgon Activated Carbon (Eriez Magnetics) by Atmospheric Zadra Elution for 30 Hours.
Loading conditions: 5 g carbon in 1L of 250 mg/L Au solution @ 25°C, pH of 10 and a shaker rpm of 180 for 24 hours. Elution conditions: 0.5% NaCN and 1% NaOH in 0.5L @ pH of 12.8 and 98°C.

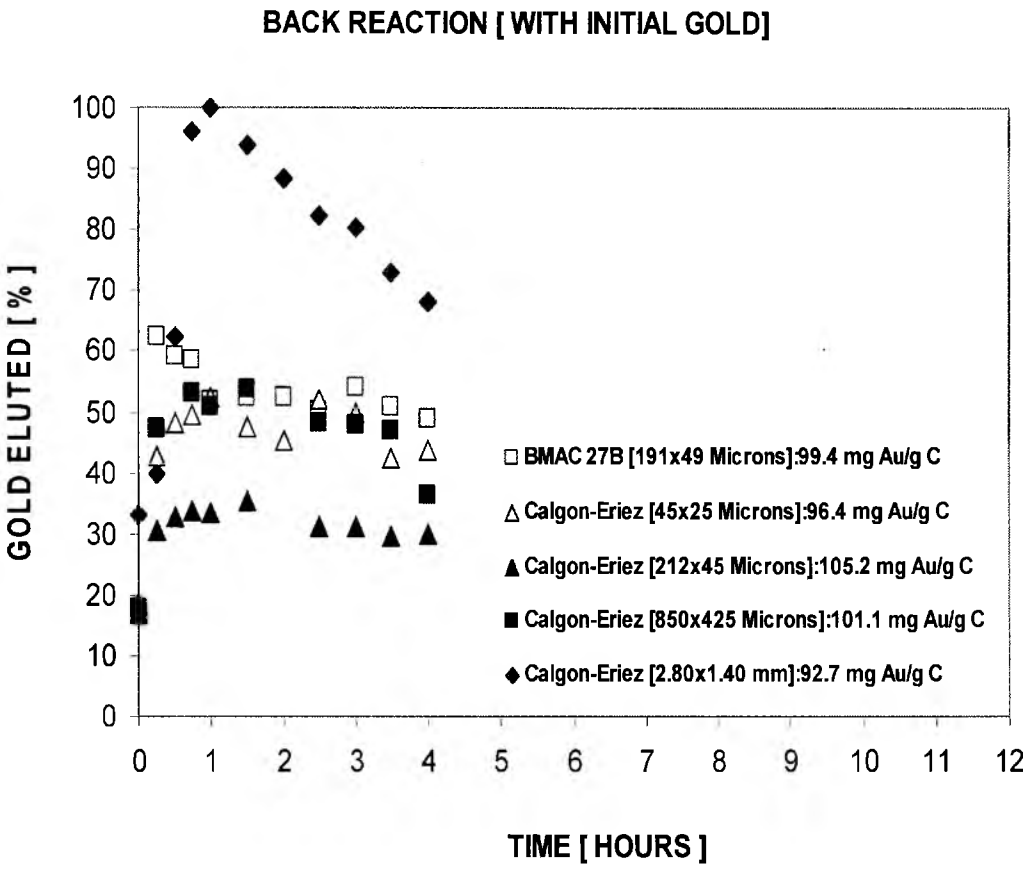


Figure 21 Rate of Elution (Back-reaction with Initial Gold Concentration of 150 ppm) of Calgon and BMAC 27B Carbons (Eriez Magnetics).
Loading conditions: 2 g carbon in 0.5L of 500 mg/L Au solution @ 25°C, pH of 10.81 and a shaker rpm of 180 for 24 hours. Elution conditions: Presoaked for 12 minutes, 0.5% NaCN and 1% NaOH in 0.4L @ pH of 12.7 and 98°C.

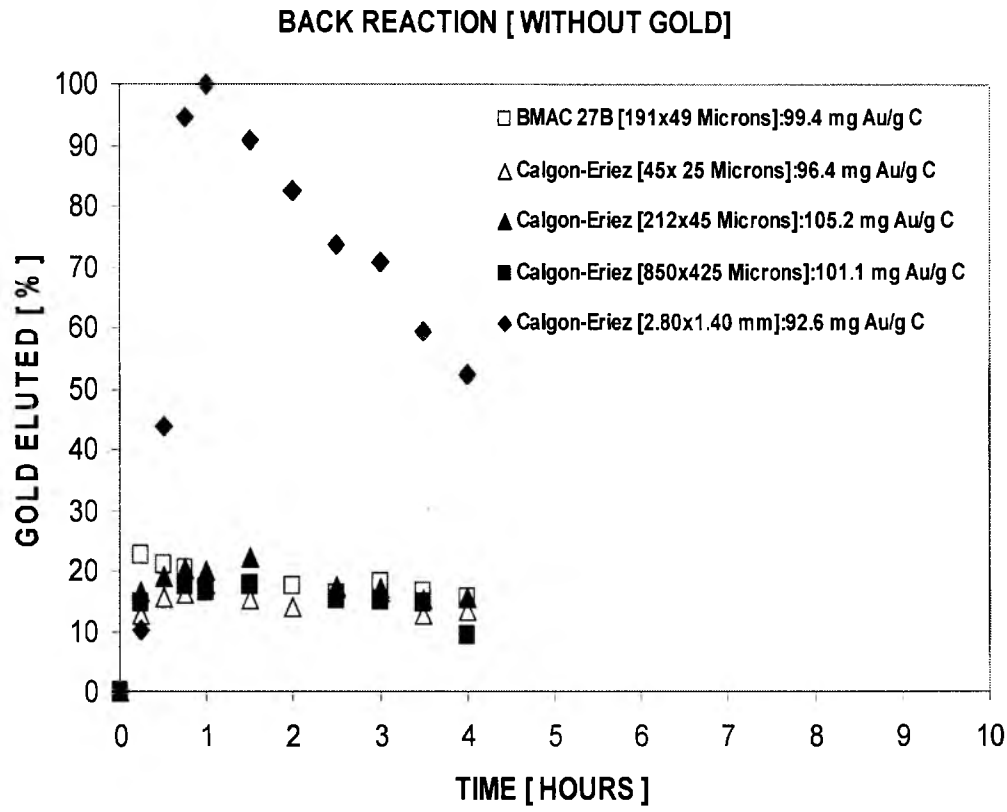


Figure 22 Rate of Elution (Back-reaction without Initial Gold Concentration) of Calgon and BMAC 27B Carbons (Eriez Magnetics).
Loading conditions: 2 g carbon in 0.5L of 500 mg/L Au solution @ 25°C, pH of 10.81 and a shaker rpm of 180 for 24 hours. Elution conditions: Presoaked for 12 minutes, 0.5% NaCN and 1% NaOH in 0.4L @ pH of 12.7 and 98°C.

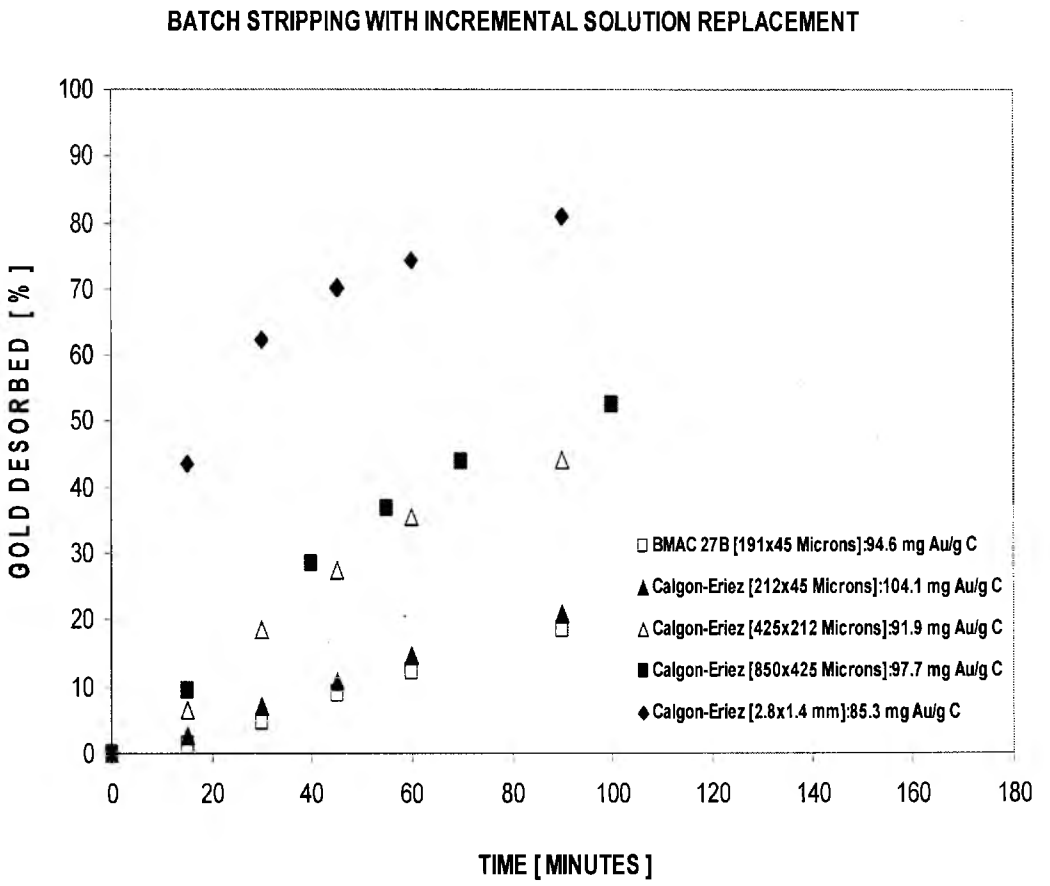


Figure 23 Rate of Elution of Calgon and BMAC 27B Carbons (Eriez Magnetics) by Atmospheric Zadra Elution.
Loading conditions: 2 g carbon in 1L of 500 mg/L Au solution @ 25°C, pH of 10.64 and a shaker rpm of 180 for 24 hours. Elution conditions: Presoaked for 15 minutes, 0.5% NaCN and 1% NaOH in 0.2L/sample time @ pH of 12 and 100°C.

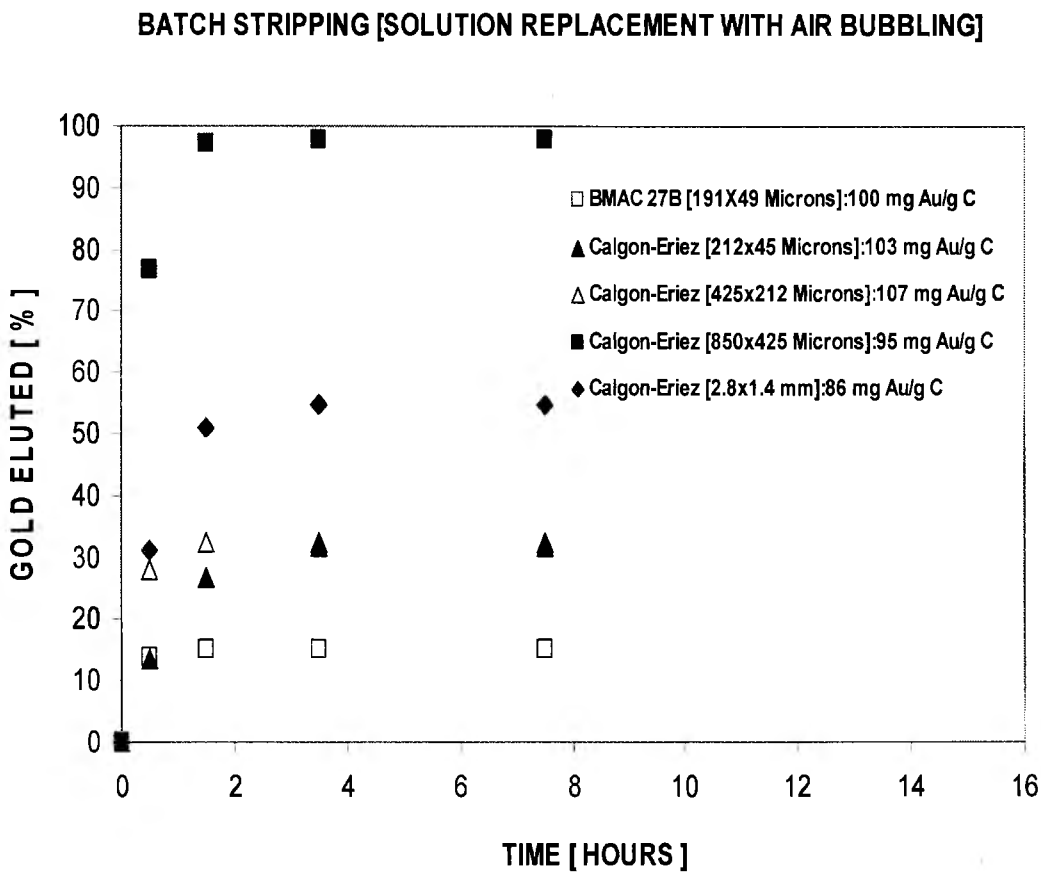


Figure 24 Rate of Elution of Calgon and BMAC 27B Carbons (Eriez Magnetics) by Atmospheric Zadra Elution with Air-bubbling into Strip Solution. Loading conditions: 1 g carbon in 0.5L of 500 mg/L Au solution @ 25°C, pH of 11 and shaker rpm of 180 for 24 hours. Elution conditions: Presoaked for 30 minutes with 0.5% NaCN, 1% NaOH @ pH of 10.88; stripped with same solution @ 0.2L/sample cycle @ 100°C.

particles the faster the stripping rate, with the granular carbon eluting on average above 70% under all the stripping conditions considered. It can seen that the GAC (2.8 x 1.4 mm) eluted better under both shorter stripping times of 1 to 1.5 hours (Figures 18 and 23) and longer stripping times of up to 30 hours (Figures 17, 19, and 20), suggesting that time is probably not the factor limiting the rate of elution of the finer carbon samples.

Unlike the rate of adsorption results presented in the preceding section which showed consistency with the inverse dependence of rate on particle size; the results of the stripping reaction by the atmospheric Zadra method are clearly inconsistent with the expectation that rate of reaction is inversely dependent on particle size. It was expected that the finer carbon particles with relatively larger external surface areas in contact with the strip solution will strip faster than the GAC with relatively smaller surface areas in contact with the strip solution. The expected trend was for the finest carbon sample, the 212 x 45 μm size fraction, to have striped faster than all the carbon samples; with the GAC sample stripping the least amount of gold at the slowest rate. However, this was not the case as indicated by the results. Furthermore, the stripping behavior of the finer carbons is rather unusual and anomalous with the view that rate of reaction is dependent on temperature.

It is worth pointing out that although the strip solution temperature was maintained at boiling point for all the different size fractions of carbon stripped, the results reveal that the finer carbons did not respond favorably to temperature under the various stripping conditions used for the Zadra method. In fact, the average percent gold eluted from the finer carbons under the various stripping condition is estimated to be

around 42. It was expected that a high strip solution temperature would drive the stripping reactions of all the carbons favorably, especially the finer carbon reactions.

The unusual stripping behavior of the finer carbons at the high strip solution temperature suggests that other factors in addition to particle size and temperature are required to effectively strip gold cyanide from activated carbons. This demonstrates that the factors (particle size, temperature, pressure, and strip solution composition) which influence the stripping reaction are interdependent in the influence they have on the stripping reaction, and they must be set at their appropriate levels in order to optimize the rate of elution and the amount of gold stripped.

In order to determine if gold concentration in the aqueous strip solution influences the rate of elution experiments were performed by adjusting the concentration of the initial strip solution with gold cyanide. However, the batch-continuous stripping results presented in Figure 21, clearly show that the GAC has yet again stripped faster than the other carbon samples. It is worth pointing out that adjusting the concentration of the strip solution with gold did significantly influence the stripping of the GAC sample by 10-30 percent increase over the preceding results in Figures 17-20. As Figures 21 and 22 indicate, the GAC attained 100% stripping during the first hour. However, the extent of stripping started to decrease after the 1 hour.

Comparing Figure 21 and Figures 17-20, it is evident that adjusting the aqueous strip solution with initial gold concentration led to an initial rapid increase in the extent of stripping of the GAC during the first hour; followed by a somewhat gradual decrease in the extent of stripping with time. This appears to indicate that the initial rapid rate of elution may be controlled by surface reaction in which the initial gold in the strip solution

may have forced the adsorbed gold on the surface sites of the GAC into solution. The gradual decrease in the extent of elution with time as seen in Figure 21 suggests that most of the adsorbed gold has been stripped from the most accessible sites on the GAC. At this stage, the stripping reaction is probably controlled by pore diffusion, where the strip solution has to diffuse into these longer pores distances of the carbon (given that the carbon is granular and has longer diffusion distances, and the strip solution for that matter has to travel slowly through these pores to reach the adsorbed gold cyanide) to force adsorbed gold in these pores into solution. This is a slow process considering the fact that the solution mixture was not stirred; rather agitation of the solution mixture in the reaction vessel was achieved through the bubbling effect of boiling. This may have accounted for the gradual decrease in the extent of stripping with time.

It is worth noting that both Figures 21 and 22 show that adjusting the initial concentration of strip solution did not improve the extent of stripping of the finer carbons. In fact Figure 22, which shows a plot of percent gold eluted without initial gold versus time, reveal that the finer carbons did not elute much gold as compared to the results shown Figures 19 and 20. The average percent of gold eluted by the finer carbons in this case is less than 21. This is below the average percent gold eluted by the finer carbons as shown in Figures 19 and 20, which is about 40%. This clearly shows that the initial gold adjustment rather than facilitating the stripping of the finer carbons impeded their stripping. In general, the most plausible reason for the unusual stripping behavior of the finer carbons among other considerations (such as the application of pressure in combination with the temperature effect of the boiling process), may be the inability of the strip solution to force adsorbed gold locked up in the pores (especially the micropores

which may be characteristic of the very fine carbon particles) of the finer carbons out into solution.

Furthermore, although the notion that gold may be adsorbed in a partially reduced form of gold clusters on the carbon (54) has been discarded, some stripping experiments were done by bubbling air continuously into the strip solution during the stripping process. The results of this experiment are presented in Figure 24. The results show that with the exception of the 850 x 425 μm sample, the stripping rates of the other carbon samples including the GAC are not improved, with the GAC eluting only 50% of its gold in 7.5 hours. The anomalous stripping behavior of the 850 x 425 microns size fraction is not well understood as repeat experiments were not conducted for verification.

The results suggest that factors such as the volume of strip solution used in the elution process, the occurrence of a back reaction during stripping, and gold cyanide been adsorbed in the reduced form on the carbons are not factors which influence the rate of elution of the finer carbons as these were verified. Using a different strip solution such as the Davidson (10% KOH and 5% K_2CO_3) or the AARL (1% NaOH and 3% NaCN) strip solutions could have presented a different outcome; however, this was not done.

In summary, it has been demonstrated using different stripping conditions that under the atmospheric Zadra elution method (atmospheric pressure and elevated temperatures); the rate of gold cyanide elution is the fastest for the granular activated carbon when compared to the finer activated carbons and BMAC 27 B. Of course, the stripping results for the Zadra elution method are not expected since they are clearly inconsistent with the expectation that, rate of reaction is inversely dependent on particle size. What the results appear to suggest is that a number of factors account for the

effective stripping of gold cyanide from activated carbons. In other words, the factors (particle size, temperature, pressure, and strip solution composition) which influence the stripping reaction are interdependent and must be set at their appropriate levels in order to optimize the elution rate of reaction and the amount of gold stripped.

3.4.2 Syringe and Hydraulic Press Stripping Method

Boiling strip solution (1% NaOH, 0.5% NaCN and pH 13) at an estimated pressure and flow rate of 42 psi and 13 ml/minute respectively was mechanically forced through a bed of activated carbon in a syringe by a Carver laboratory hydraulic press. The results are presented in Figure 25. A total of 24-bed volumes (bed volume is 50 ml) of strip solution and 2-bed volumes of boiling DI-water was passed through each carbon sample; the boiling DI-water was meant to remove any residual gold from the carbon samples. The results for the various particle sizes shown in Figure 25 clearly depart from the trend obtained with the atmospheric Zadra stripping process.

Unlike the Zadra method, with the syringe and hydraulic press method the fine carbon particles were eluted at a much faster rate as expected. While the GAC eluted only 30% of its total adsorbed gold in 1.2L of the strip solution, the 425 x 212 μm and 212 x 45 μm samples eluted 80% in the same volume of strip solution.

With the exception of the MAC, Figure 25 shows that as the AC particles decrease in size the elution rate increases. Figure 25 presents a clear trend in the rate of

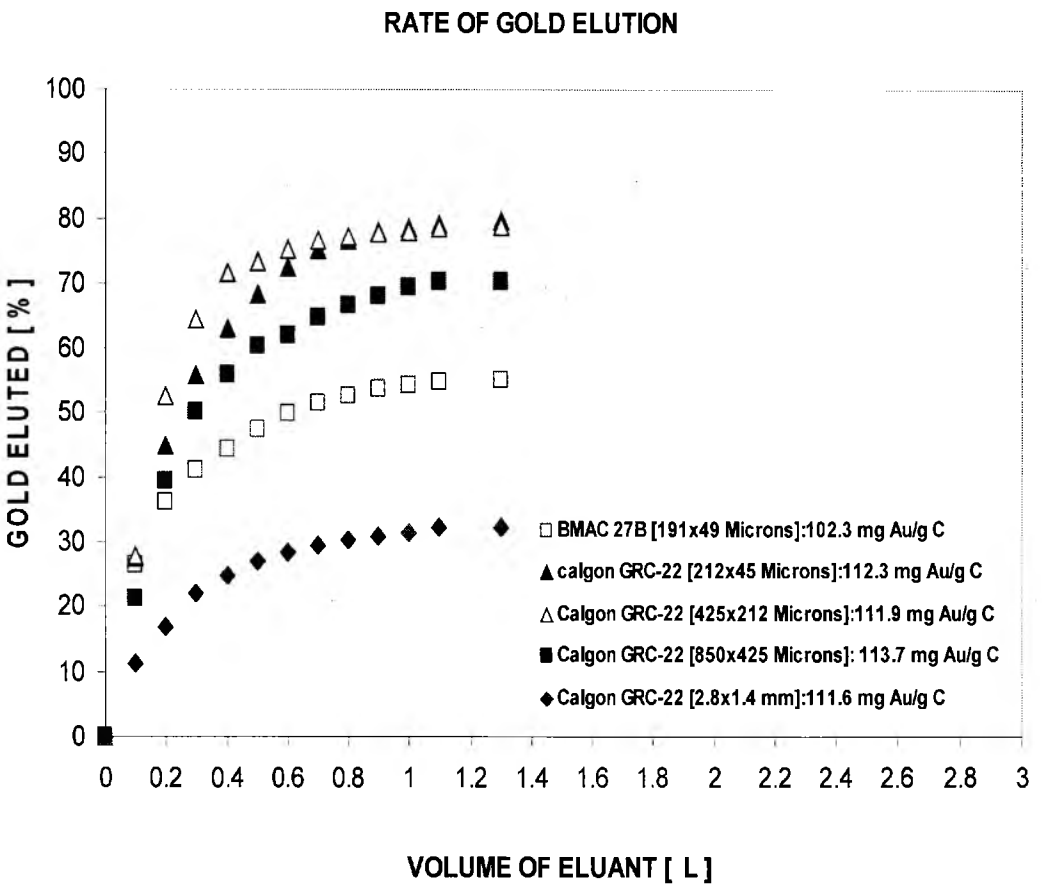


Figure 25 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnettics) Carbons by the Syringe and Hydraulic Press Method using Zadra Solution.
Loading conditions: 5 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.91 and a shaker rpm of 220 for 24 hours. Elution conditions: Estimated average flow rate of 13 ml/minute and pressure of 42 psi; 1 g AC presoaked for 20 minutes with 3% NaOH, 1% NaCN @ pH 13; stripped with 1.1L of same solution @ 0.1L/sample cycle; rinsed with 0.2L boiling DI-water, strip temperature: 98°C.

stripping of the sized AC particles, substantiating the fact that the stripping reaction is not independent of particle size. Again, the rate of stripping of the MAC has not been improved under this method. The hydraulic press was replaced with a syringe pump as it was difficult to use and also for the avoidance of experimental errors.

To summarize, unlike stripping under the atmospheric Zadra elution, a trend with respect to particle size in the rate of elution of gold is evident with the syringe and hydraulic press stripping method. The results show that a distinct correlation exist between the rate of stripping of gold cyanide from AC and particle size; it is evident that as AC decreases in size the rate of gold cyanide elution increases. The results clearly demonstrate the inverse dependence of particle size on the stripping reaction.

3.4.3 Syringe Pump Stripping Method

The syringe pump was used to force strip solution at a flow rate of 15/26 ml/minute and a calculated minimum pressure of 36 psi through a bed of carbon samples in a syringe. As has already been stated in section 3.4, it is the expectation that the stripping reaction under this method of stripping will be consistent with view that rate of reaction in inversely dependent on particle size. The results for the syringe pump elution are presented in Tables 13 and 14, and Figures 26 to 28. The stripping conditions specific to each experiment are indicated in the figure captions. Figures 26 and 27 are the results for stripping with Zadra solution (1% NaOH and 0.5% NaCN) at 75°C and 98°C respectively.

Table 13
Effect of Temperature (at 75 and 98°C) and Particle Size on Elution of Calgon GRC 22 and BMAC 27B Carbons by the Syringe Pump Method using Zadra Solution.

Particle size	Percent gold eluted at 75°C	Percent gold eluted at 98°C	Percent difference of gold eluted
Calgon GRC 22 [2.80 x 1.40mm]	42.5	39.0	-3.5
Calgon GRC 22 [850 x 425μm]	52.2	75.0	22.8
Calgon GRC 22 [425 x 212μm]	58.3	80.7	22.4
Calgon GRC 22 [212 x 45μm]	73.0	81.3	8.3
BMAC 27B [191 x 49 μm]	59.0	72.1	13.1

Loading conditions: 5 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.91 shaker rpm of 220 for 24 hours. Elution conditions: Average flow rate of 15/26 ml/minute, minimum pressure of 36 psi; 1 g AC presoaked for 30/10 minutes with 1% NaOH, 0.5% NaCN @ pH 13; stripped with 1L of same solution @ 0.2L/sample cycle; rinsed with 0.1L boiling DI-water; strip temperature: 75 and 98°C; total number of bed volumes of strip solution and DI-water passed through each sample was 22/24 @ 3/4 minutes/bed volume.

Table 14
Effect of Strip Solution on Elution of Calgon GRC 22 and BMAC 27B Carbons (Zadra and Davidson Solutions Compared using Syringe Pump Elution Method).

Particle size	Percent gold eluted by Zadra solution at 98°C	Percent gold eluted by Davidson solution at 98°C	Percent difference of gold eluted
Calgon GRC 22 [2.80 x 1.40mm]	39.0	96.9	57.9
Calgon GRC 22 [850 x 425µm]	75.0	99.3	24.3
Calgon GRC 22 [425 x 212µm]	80.7	99.8	19.1
Calgon GRC 22 [212 x 45µm]	81.3	99.8	18.5
BMAC 27B [191 x 49 µm]	72.1	99.4	27.3

Loading conditions [Zadra and Davidson]: 5 and 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and shaker rpm of 220 for 24 hours. Elution conditions for Zadra: Flow rate @ 26 ml/min, minimum pressure of 36 psi, 1 g AC pre-soaked for 10 minutes with 1% NaOH, 0.5%NaCN of pH 11.3; stripped with 1L of same solution @ 0.2L/sample cycle; rinsed with 0.1L boiling DI-water; strip temperature: 98°C; total number of bed volumes of strip solution and DI-water passed through each sample was 22 @ 3 minutes/bed volume. Elution conditions for Davidson: flow rate @ 23 ml/min, minimum pressure of 36 psi;1 g AC pre-soaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 2L DI-water @ 0.4L/sample cycle @ 98°C total number of bed volumes of strip solution passed through each sample was 40 @ 3 minutes/bed volume.

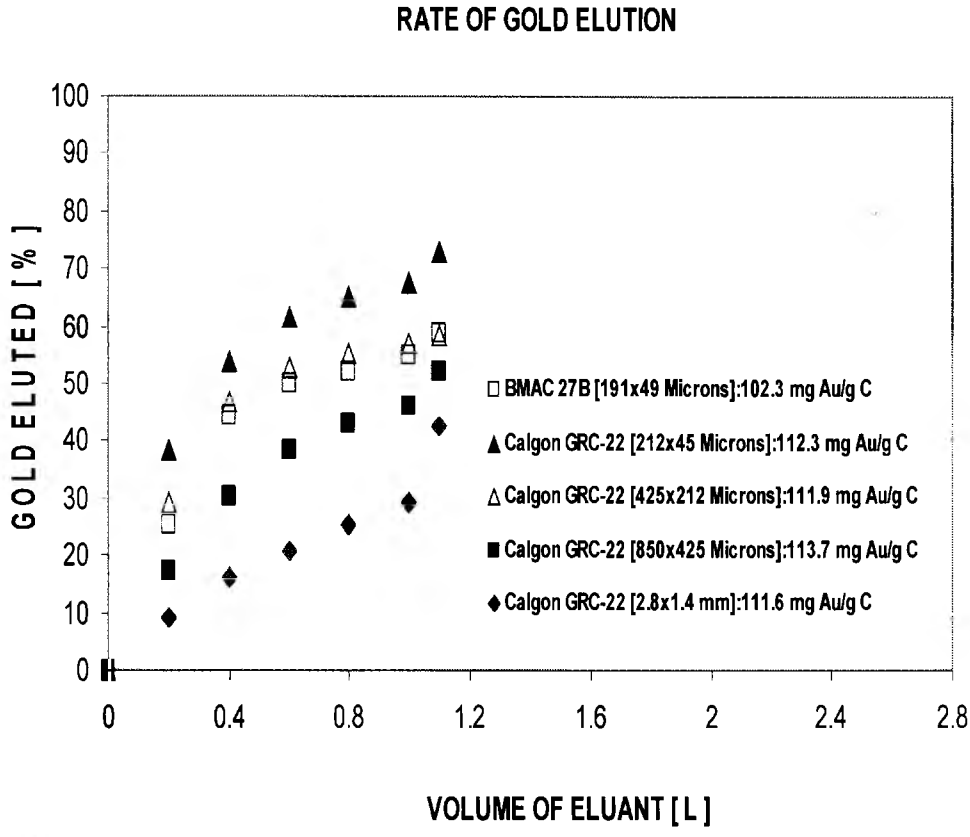


Figure 26 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Syringe Pump Method using Zadra Solution at 75°C.
Loading conditions: 5 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.91 shaker rpm of 220 for 24 hours. Elution conditions: Average flow rate of 15 ml/minute, minimum pressure of 36 psi. 1 g AC presoaked for 30 minutes with 1% NaOH, 0.5% NaCN @ pH 13; stripped with 1L of same solution @ 0.2L/sample cycle; rinsed with 0.1L boiling DI-water; strip temperature of 75°C.

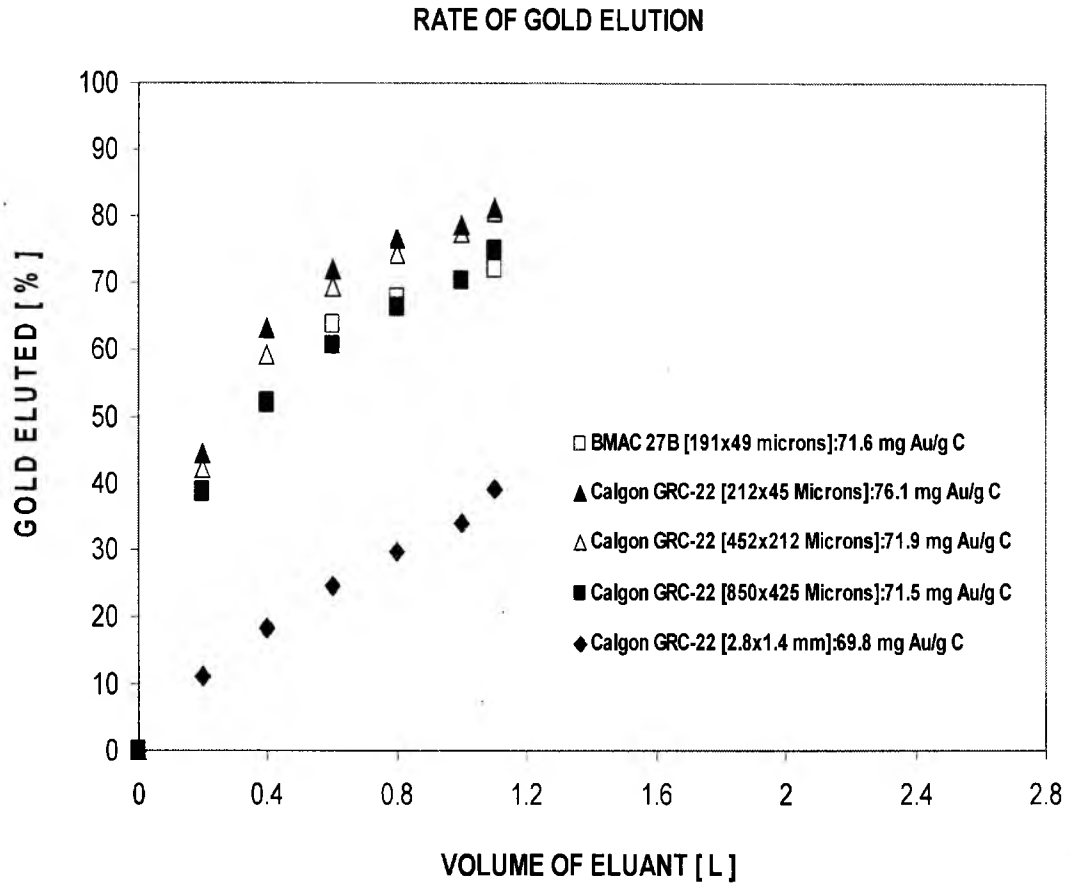


Figure 27 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Syringe Pump Method using Zadra Solution at 98°C.
Loading conditions: 5 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and shaker rpm of 220 for 24 hours. Elution conditions: Flow rate @ 26 ml/min, minimum pressure of 36 psi. 1 g AC presoaked for 10 minutes with 1% NaOH, 0.5%NaCN of pH 11.3; stripped with 1L of same solution @ 0.2L/sample cycle; rinsed with 0.1L boiling DI-water; strip temperature: 98°C.

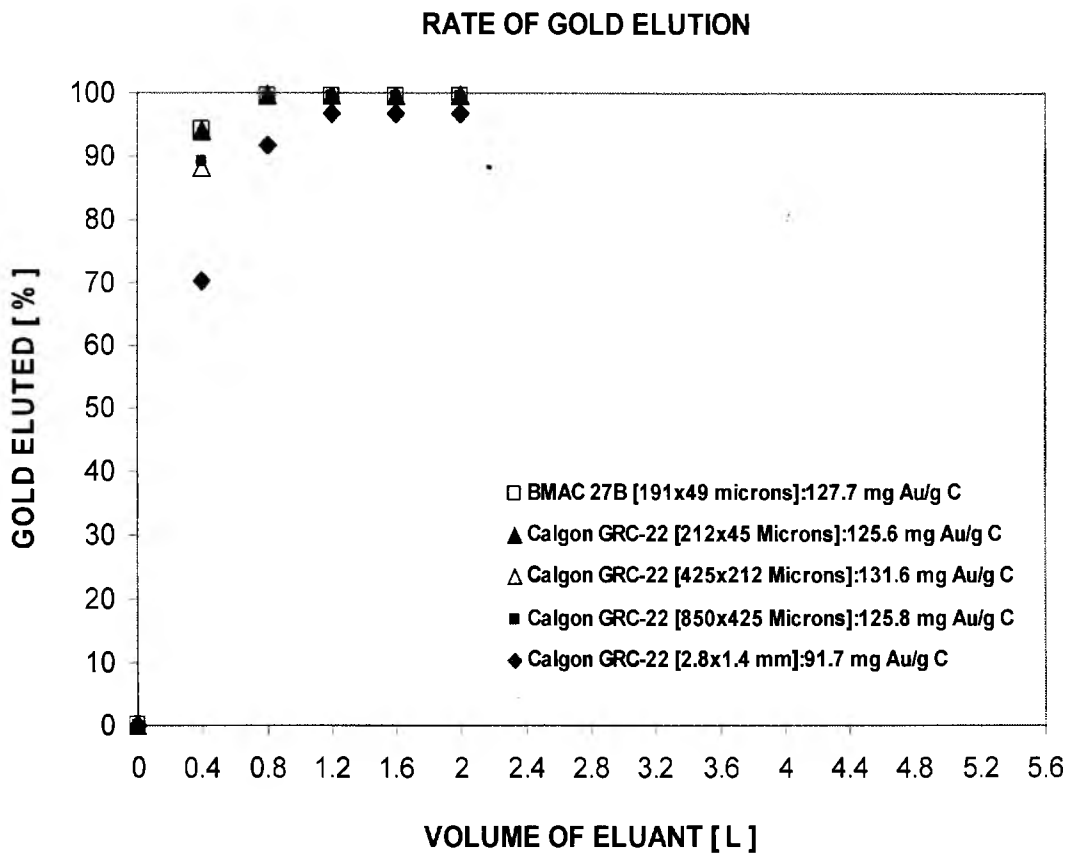


Figure 28 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Syringe Pump Method using Davidson Solution at 98°C.
Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: flow rate @ 23 ml/min, minimum pressure of 36 psi. 1 g AC presoaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 2L DI-water @ 0.4L/sample cycle @ 98°C.

The flow rates for the two experiments were 15 and 26 ml/minutes respectively; and this was due to the fact that different filter membranes were used for the two experiments. A 0.2 μm filter membrane was used for the experiment conducted at 75°C and a 0.45 μm filter membrane was used for the 98°C experiment. Figure 28 on the other hand presents results for stripping with Davidson strip solution (10% KOH and 5% K_2CO_3) at 98°C. Again as in the preceding section, Figures 26 and 27 show a trend in the stripping process.

It is evident from Figures 26 and 27, and Table 13 that the size of carbon particles does have an effect on the rate of stripping, with the finer carbon samples eluting faster than the coarser samples; demonstrating that the rate of elution of gold cyanide from AC is strongly influenced by carbon size. The expectation that the rate of elution of gold cyanide from AC is dependent on the AC particle size and that as the AC size decreases the rate of elution increases, is reinforced by the results presented Figure 28, for the Davidson elution method. It is worth noting that while all the carbon samples shown in Figure 28, stripped nearly 100% of their total adsorbed gold in 40-bed volumes of strip solution; the finer carbons eluted on average 90% of their gold in the first bed volume (400 ml of strip solution), while the GAC eluted 70% in the same volume of strip solution; reinforcing the notion that the finer the carbon the faster the rate of elution.

The effect of temperature on the stripping rate is demonstrated in Table 13 for two different temperatures (75 and 98°C) in which case the Zadra solution with the syringe pump were used. Clearly, Table 13 shows how influential temperature is on the rate of stripping. In fact, the finer carbon samples eluted between 10 and 20% more adsorbed gold with the 23°C increase in temperature. The anomalous behavior (4 percent reduction

in amount of gold adsorbed with 23°C increase in temperature) of the GAC in Table 13 can be attributed to experimental error.

The effect of strip solution composition on the rate of gold elution is presented in Table 14. The carbon samples, as Table 14 indicates, were stripped at the same temperature (98°C), however, with two different strip solutions; the Davidson solution (10% KOH and 5% K_2CO_3) and the Zadra solution (1% NaOH and 0.5% NaCN). The percentage difference in the amounts of adsorbed gold stripped (19-58%) by using different strip solutions (Zadra and Davidson solution) at the same temperature is significant. It is clear from Table 14 that by just switching from the Zadra solution to Davidson solution in the elution process, more gold has been stripped (between 19-58%). It is evident from the results presented that stripping with the Davidson solution is faster and more efficient than with the Zadra solution for all the AC samples studied. In particular, GAC eluted only 39% of its total adsorbed gold with the Zadra solution; however, with the Davidson solution GAC yielded 97% of its adsorbed gold. This further suggests that the Davidson strip solution favors both the GAC and the finer carbon particles, that is, under suitable conditions, the Davidson solution will strip all sizes of carbon particles loaded with gold cyanide.

The Davidson solution is worth considering for the treatment of gold ores. Even though the reasons for the effectiveness of the Davidson strip solution over the Zadra strip solution were not verified; it is worth pointing out that this research has demonstrated that the Davidson strip solution has two distinct advantages over the Zadra solution. Apart from its ability to strip all size fractions of carbon; it is only used for presoaking the carbon after which the gold is flushed out with water. Of course apart

from economic considerations, further work has to done to identify the factors that account for the Davidson solution's efficiency.

The rate of elution of the BMAC 27B improves significantly with the Davidson solution as can be seen in all the results presented for this section. Specifically, it had elution rates comparable with other activated carbons as shown in Figure 28.

In summary, it has been demonstrated by these results presented in the section that under suitable stripping conditions, particle size, temperature and strip solution composition affect the rate of gold elution. That is, the rate and amount of gold eluted from loaded AC/MAC is highly influenced by the AC/MAC particle size, the stripping temperature, and the composition of the strip solution used in the stripping process. Again the results of this section reinforce the results of the preceding section that the stripping reaction is inversely dependent on carbon particle size.

3.4.4 Filter Press Elution Method

The Davidson, AARL, and Zadra stripping solution were used under this method of stripping for evaluating the elution rate in terms of AC particle size and other process variables such as temperature, pressure and composition of strip solution. Again it is expected that the stripping reaction will be inversely dependent on the carbon particles and directly dependent on the temperature of the strip solution.

The Davidson stripping solution was studied at three different temperatures (25°C, 60°C and 98°C). A total of 4 bed volumes (a bed volume is taken as 1 L) of strip solution was used for each of the samples stripped at 25 and 98°C, respectively, while 2 bed volumes of strip solution was used for the sample stripped at 60°C.

The AARL and Zadra solutions were evaluated at 98°C and 25°C, respectively. While a total of 4 bed volumes of AARL solution was used to strip each sample at a stripping temperature of 98°C, 2 bed volumes of Zadra solution was used for stripping each sample at 25°C. The results are presented in Figures 29 to 32 and Tables 15 to 17. Figures 29 to 31 and Table 15 are results presented for the Davidson stripping solution while Figure 32 depicts stripping with the AARL solution.

The effect of particle size, temperature, and strip solution composition on the rate of gold elution is shown in Tables 15 and 16 respectively. In addition, under the filter press method of stripping, Table 17 shows the results of stripping with Zadra solution at room temperature. Again as in the preceding sections, that is, under the syringe and hydraulic press and syringe pump elution methods, Figures 29 to 31 and Table 15 demonstrate that particle size has an effect on the stripping of gold cyanide from activated carbon. It is apparent from Table 15 that as AC size decreases, the rate of gold elution increases; reinforcing the expectation that the rate of gold cyanide desorption from AC/MAC is inversely dependent on activated carbon particle size.

The effect of temperature on the stripping reaction is evident in Figures 29 to 31 and Table 15. It is clear from Table 15 (as in section 3.4.2) that the rate of gold cyanide elution is dependent on temperature. It is observed that as the stripping temperature decreases from 98°C to 25°C, the elution reaction rate decreases significantly. A 38°C (from 98 to 60°C; using 4 and 2 bed volumes of strip solution for each sample respectively) decrease in the stripping temperature corresponds to an estimated 51% decrease in the extent of elution rate; and a 73°C (98 to 25°C; using 4 bed volumes of

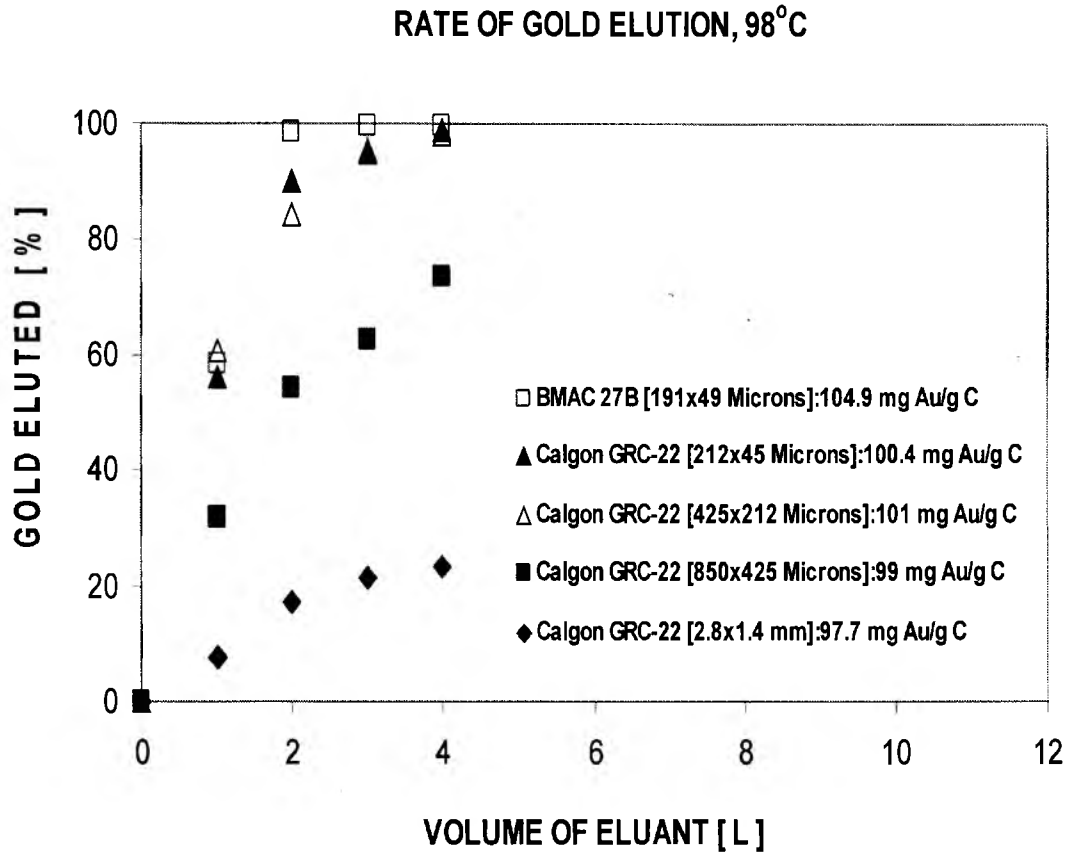


Figure 29 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using Davidson Solution at 98°C.
Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC presoaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 4L tap water @ 1L/sample cycle @ 98°C.

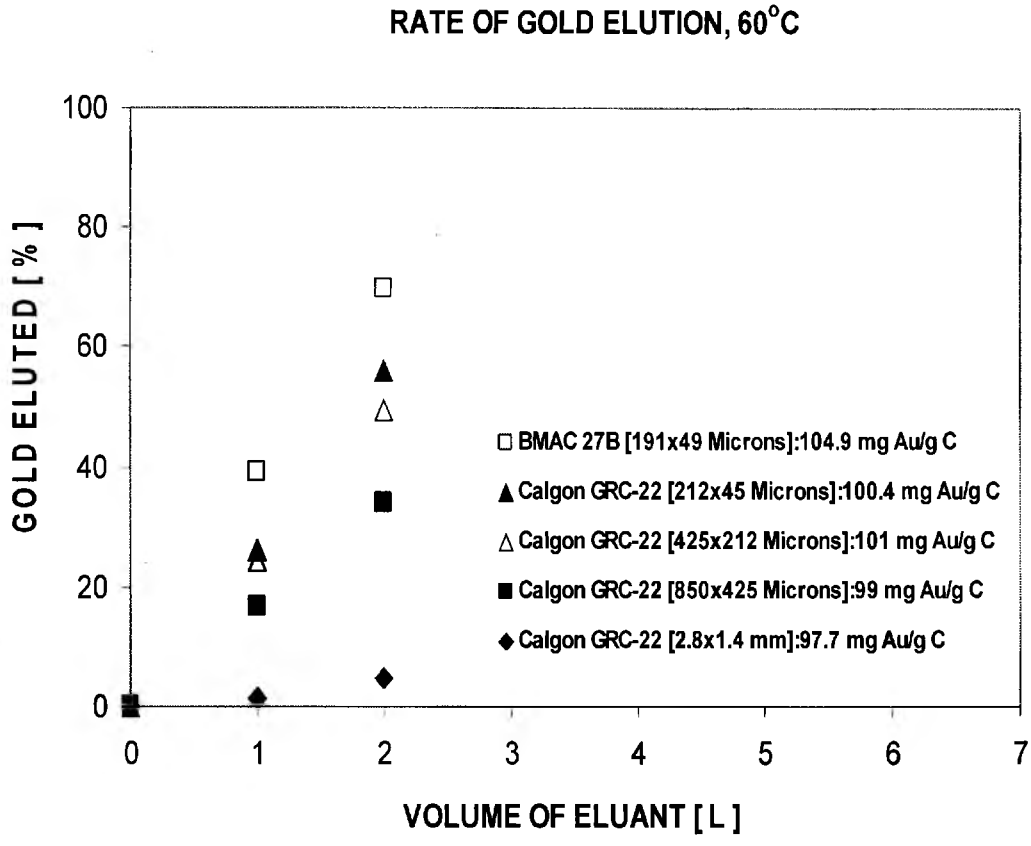


Figure 30 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using Davidson Solution at 60°C.
Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC presoaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 2L tap water @ 1L/sample cycle @ 60°C.

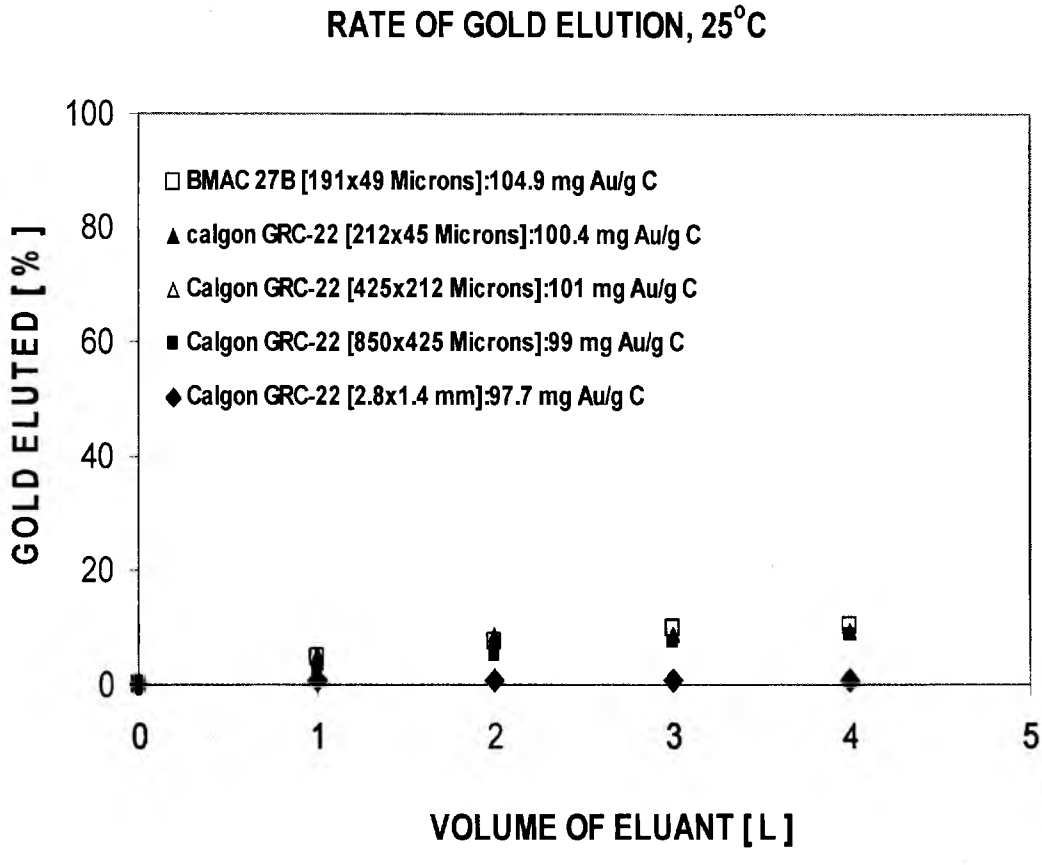


Figure 31 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using Davidson Solution at 25°C.
Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC presoaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 4L tap water @ 1L/sample cycle @ 25°C.

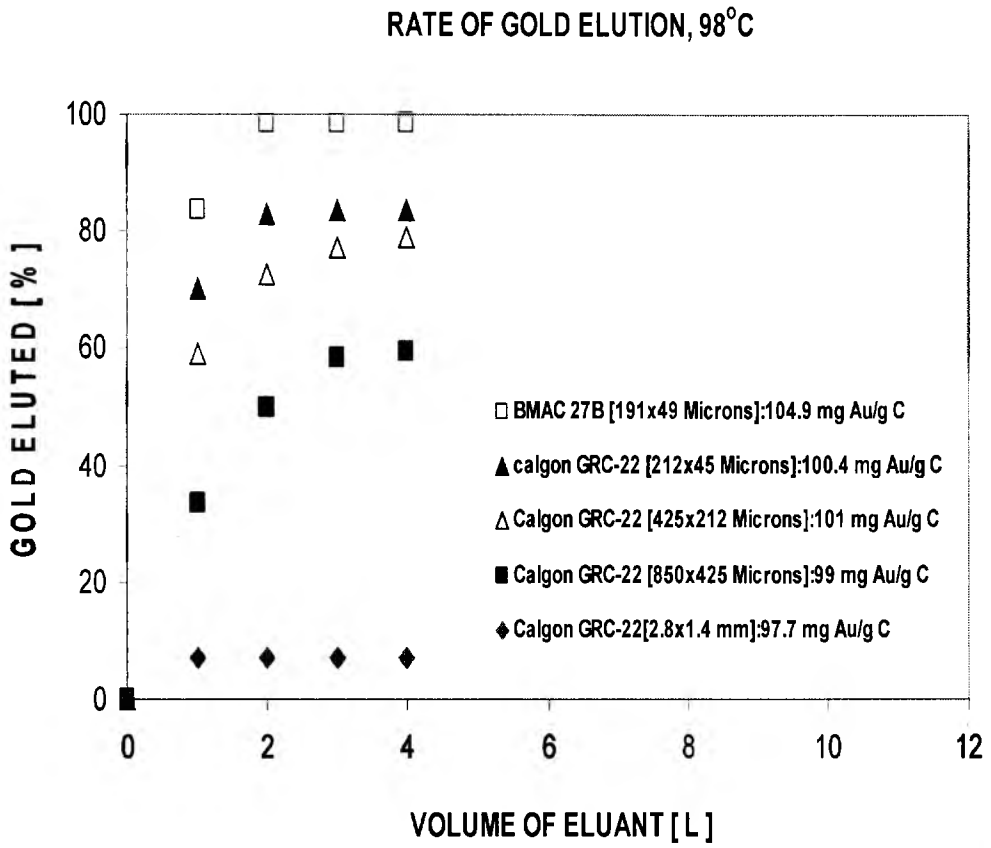


Figure 32 Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using AARL Solution at 98°C.
Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC presoaked for 30 minutes with 1%NaOH, 3% NaCN @ pH 12; stripped with 4L tap water @ 1L/sample cycle @ 98°C.

Table 15
Effect of Particle Size and Temperature on Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using Davidson Solution at Different Temperatures.

Particle size	Percent gold eluted per volume of strip solution		
	98°C	**60°C**	**25°C**
Calgon GRC 22 [2.80 x 1.40mm]	23.3	4.7	**0.9**
Calgon GRC 22 [850 x 425µm]	73.5	33.9	**8.7**
Calgon GRC 22 [425 x 212µm]	98.3	49.5	**8.9**
Calgon GRC 22 [212 x 45µm]	99.0	56.1	**9.2**
BMAC 27B [191 x 49 µm]	99.1	69.7	**10.1**

Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 2-4L tap water @ 1L/sample cycle @ 25 98°C; total number of bed volumes of strip solution [tap water] passed through each sample was 2-4 @ less than a minute/bed volume.

Table 16
Effect of Strip Solution on Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by Filter Press Method (AARL and Davidson Strip Solutions Compared).

Particle size	Percent gold eluted by AARL solution at 98°C	Percent gold eluted by Davidson solution at 98°C	Percent difference of gold eluted
Calgon GRC 22 [2.80 x 1.40mm]	7.1	23.3	16.2
Calgon GRC 22 [850 x 425µm]	59.4	73.5	14.1
Calgon GRC 22 [425 x 212µm]	79.0	98.3	19.3
Calgon GRC 22 [212 x 45µm]	83.8	99.0	14.8
BMAC 27B [191 x 49 µm]	98.7	99.1	0.4

Loading conditions [Davidson and AARL]: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours.
Elution conditions for Davidson: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 4L tap water @ 1L/sample cycle @ 98°C; total number of bed volumes of strip solution [tap water] passed through each sample was 4 @ less than a minute/bed volume.
Elution conditions for AARL: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes with 1%NaOH, 3% NaCN @ pH 12; stripped with 4L tap water @ 1L/sample cycle @ 98°C; total number of bed volumes of strip solution passed through each sample was 4 @ less than a minute/bed volume.

Table 17
Rate of Elution of Calgon GRC 22 (Calgon Corporation) and BMAC 27B (Eriez Magnetics) Carbons by the Filter Press Method using Zadra Solution at 25°C.

Particle size	mg Au/g C loaded	mg Au/g C eluted	Percent total Au eluted
Calgon GRC 22 [2.80 x 1.40mm]	97.7	0.20	0.20
Calgon GRC 22 [850 x 425µm]	99.0	1.11	1.10
Calgon GRC 22 [425 x 212µm]	101.0	2.00	1.98
Calgon GRC 22 [212 x 45µm]	100.4	5.00	4.98
BMAC 27B [191 X 49 µM]	104.9	9.6	9.15

Loading conditions: 7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52 and a shaker rpm of 220 for 24 hours. Elution conditions: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes and stripped with 2L of 1% NaOH, 0.5% NaCN @ pH 11.8, 2L/sample cycle @ 25°C; total number of bed volumes of strip solution passed through each sample was 2 @ less than a minute/bed volume.

strip solution for each sample at the respective temperatures) decrease in the stripping temperature corresponds to and estimated 81% reduction in the extent of elution. These results reinforce the results of section 3.4.2 that the stripping of gold cyanide from activated carbons is favored by both increasing temperature of the strip solution and decreasing particle size of the carbon. The effect of temperature on stripping rate of reaction is again evident in the Zadra stripping (conducted at 25°C) results shown in Table 17. It is worth noting that, even though a pressure of 80 psi was applied in the Zadra elution at room temperature as in all cases under this stripping method, the percent gold eluted was less than 10. This suggests that pressure alone is not sufficient to drive the elution reaction.

The effect of strip solution composition on the extent of stripping is presented in Table 16. In this instance, two strip solutions; the AARL (1% NaOH and 3% NaCN) and Davidson (10% KOH and 5% K_2CO_3) strip solutions were used for stripping at 98°C. It is evident from Table 16 that the Davidson strip solution is more effective in stripping gold cyanide from the carbons than the AARL strip solution. The results are consistent with the results of the preceding section, that the strip solution composition has an important effect on the rate and amount of gold stripped. Just like in the preceding section the reasons for the effectiveness of the Davidson strip solution over the AARL solution were not determined. However, what is clear is the Davidson strip solution just like the AARL solution is only used to presoak the gold-loaded carbon, after which the gold is flushed out with ordinary water. If this is the case for the two strip solutions, and yet the Davidson solution is more effective in stripping gold cyanide from activated carbons than both the AARL and Zadra solutions, then it is a strip solution worth considering for the

treatment of gold ores. Of course economic considerations must be taken into account and further work must be done to identify the factors that account for the efficiency of the Davidson solution.

The rate of elution of gold cyanide from BMAC 27B is excellent using this stripping method. BMAC 27B had the fastest elution rate as shown in Tables 15 and 16, and had a comparable stripping rate with the finer AC samples as indicated in Figure 29. The fast adsorption and elution rates exhibited by the MAC in section 3.3 and this section demonstrate the potential it has to replace GAC especially for the treatment of preg-robbing gold ores.

In summary, the results of this section reinforces the results of the preceding section (3.4.2) that the rate and extent of elution is highly favored by decreasing particle size, increasing temperature, and type of strip solution used in the stripping process. In addition, it has also been shown that pressure alone will not drive the elution reaction. Finally; MACs adsorptive and desorptive capabilities discussed in this section and the preceding section demonstrates that MAC has the potential to replace GAC especially for preg-robbing gold ores treatment.

3.4.5 Summary and Discussion

Carbon adsorption has been the favored route for gold processing in the past few decades after Zadra first demonstrated in the 1950s that it was possible to recover gold from leach solutions with carbon (16). Progress has since been made in understanding the nature of the carbon adsorption process; in particular carbon adsorption rate and capacity. Considerable research has been devoted and reported in the literature regarding the

carbon adsorption process and the nature of the adsorption mechanism. However, the amount of research devoted to the fundamental study of elution is rather limited, with the nature of the stripping reaction not very well understood. In particular, the effect that different size fractions of activated carbon have on the stripping of adsorbed gold cyanide is not reported in the literature.

In view of this situation, four experimental techniques were used to study the effect that particle size, temperature, pressure and strip solution composition have on the adsorption and desorption of gold cyanide from activated carbon. Of the four desorption techniques employed, the three pressurized methods (syringe and hydraulic press, syringe pump and filter press methods) gave results as expected which were consistent with the view that the rate of the desorption reaction is inversely dependent on particle size. The atmospheric Zadra elution method, however, gave unexpected results inconsistent with the general view that the rate of the desorption reaction is inversely dependent on particle size. Table 18 is a summary of the results for the four stripping methods used in this research.

In Table 18, the four stripping methods used in this research have been compared on the basis of the amount of gold stripped in 0.2L of the strip solution used, and the total amount of gold stripped in a sample's stripping cycle. The numbers in brackets represent the total amount (in percent) of gold eluted from a sample in a variable number of bed volumes (ranging from 0.2 to 4L of strip solution) while the numbers without brackets are for the amount of gold stripped with a 0.2L bed volume of the strip solution.

Table 18
Summarized Comparisons of Percent Gold Eluted at 98°C by the Four Stripping Methods with a 0.2L Strip Solution and Total Amount of Gold Stripped in Brackets.

Particle size	Atmospheric Zadra	Syringe and hydraulic press	Syringe Pump		Filter Press	
	Zadra solution	Zadra solution	Zadra solution	Davidson solution	AARL solution	Davidson solution
2.8x1.4mm	80.9	16.8(32)	11.1(39)	35.1(97)	7.1(7)	17.1(23)
850x425µm	52.5	39.5(70)	38.7(75)	44.6(99)	49.9(59)	54.3(74)
425x212µm	44.1	52.7(79)	42.1(81)	44.1(100)	72.7(79)	84.5(98)
212x45µm	20.9	44.9(79)	44.3(81)	47.0(100)	82.8(84)	89.9(99)
BMAC 27B [191x49µm]	18.6	36.2(55)	38.5(72)	47.0(99)	98.6(99)	98.6(99)

Atmospheric Zadra: Loading conditions: 2 g carbon in 1L of 500 mg/L Au solution @ 25°C, pH of 10.64 and a shaker rpm of 180 for 24 hours. Elution conditions: Pre-soaked for 15minutes, 0.5% NaCN and 1% NaOH in 0.2L/sample time @ pH of 12 and 100°C.Loading conditions for the 3 pressurized stripping methods: 5-7 g carbon in 1L of 1000 mg/L Au solution @ 25°C, pH of 10.52-10.91 and a shaker rpm of 220 for 24 hours. Syringe and Hydraulic Press: Elution conditions: Estimated average flow rate of 13 ml/minute and pressure of 42 psi; 1 g AC pre-soaked for 20 minutes with 3% NaOH, 1% NaCN @ pH 13; stripped with 1.1L of same solution @ 0.1L/sample cycle; rinsed with 0.2L boiling DI-water, strip temperature: 98°C. Syringe Pump with Zadra Solution: Elution conditions: Estimated average flow rate of 13 ml/minute and pressure of 42 psi; 1 g AC pre-soaked for 20 minutes with 3% NaOH, 1% NaCN @ pH 13; stripped with 1.1L of same solution @ 0.1L/sample cycle; rinsed with 0.2L boiling DI-water, strip temperature: 98°C. Syringe Pump with Davidson Solution: Elution conditions: flow rate @ 23 ml/min, minimum pressure of 36 psi.1 g AC pre-soaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 2L DI-water @ 0.4L/sample cycle @ 98°C. Filter Press with AARL Solution: Elution conditions: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes with 1%NaOH, 3% NaCN @ pH 12; stripped with 4L tap water @ 1L/sample cycle @ 98°C. Filter Press with Davidson Solution: Elution conditions: pressure @ 80 psi, 3 g AC pre-soaked for 30 minutes with 10% KOH, 5% K_2CO_3 @ pH 13; stripped with 4L tap water @ 1L/sample cycle @ 98°C.

From the results presented in the preceding sections the following conclusions have been reached:

- Rate of stripping of gold cyanide from activated carbon has an inverse dependence on the AC particle size.
- Rate of stripping of gold cyanide from activated carbon has a direct dependence on temperature.
- The composition of the strip solution influences the stripping reaction.

The rate of stripping of gold-loaded carbon is inversely dependent on the particle size of the activated carbon. And this is reinforced by the results presented in Table 18. Apart from the atmospheric Zadra results; the three pressurized stripping results have followed a trend consistent with the inverse dependence of rate on particle size, as expected. It is worth noting that granular activated carbons (2.8 x 1.4 mm) have relatively larger particle sizes compared to fine/powdered carbons (850 μm to minus 45μm) and as a result tend to have smaller external surface areas and larger diffusion distances. On the contrary, the fine/powdered carbons exhibit larger external surface areas with smaller diffusion distances (44). It appears that in the stripping process, the stripping reaction may be controlled by pore diffusion, surface reactions, and or film diffusion depending on the size fraction of carbon being stripped and the extent of stripping. In this regard it is expected that the stripping reactions for the finer carbons may be controlled by surface reactions or film diffusion given its shorter diffusion distances, while the coarser carbons may be predominantly controlled by pore diffusion and/or surface reactions in view of longer diffusion distances.

Adsorption and desorption rates are directly dependent on temperature. The gold adsorption process is exothermic in nature; with an activation energy estimated to be 11 KJ/mol (3, 22). In contrast, the stripping reaction is endothermic and requires thermal energy to drive it. The estimated activated energy obtained by Adams for a stripping reaction is 58 KJ/mol (6), which is five times the activation energy required for the adsorption process; reinforcing the critical nature of temperature in elution. In fact, increasing temperatures have favored the stripping of gold-loaded carbons as has already been shown in Tables 13 and 15 in the preceding sections. Table 19 presents approximate activation energy results determined from initial stripping rates using the Davidson stripping method at 98, 60 and 25°C. The average initial rate for each size fraction of carbon particles was determined for the three different temperatures. Using the Arrhenius equation (equation 7); the natural logarithm of the average initial rate (obtained from the initial stripping rates in Figures 29 to 31, where it is assumed that 1L strip solution used is equivalent to 1 second) was plotted against the inverse of the temperature (Kelvin).

The activation energy was then determined from the slope of the plot. The activation energy values obtained from this research are lower than the 58 KJ/mol value obtained for elution by Adams (6). The activation energy values (20 - 36 KJ/mol) obtained suggest that the stripping process may be transport controlled [film and pore diffusions controlled] or chemically controlled (desorption of gold cyanide reaction) (55). According to Burkin, the activation energy for diffusion at 25°C is usually between 12 and 27 KJ/mol, which depends on both the solute and solvent; so that the observed critical increment of energy, Ea, for a transport controlled process, should be within the same range, about 17 KJ/mol (55).

Table 19
Approximate Activation Energies Associated with Initial Stripping Kinetics (Davidson's Method at 98, 60 and 25°C).

Carbon type	Particle size	Average Ri [S^{-1}]	Ea [KJ/mol]
BMAC 27B	191 x 49 μm	34.10	32.17
Calgon GRC-22	2.8 x 1.4 mm	3.40	20.25
Calgon GRC-22	850 x 425 μm	16.80	35.79
Calgon GRC-22	425 x 212 μm	30.00	31.82
Calgon GRC-22	212 x 45 μm	28.70	33.52

where average Ri is the average initial rate determined for the three different temperatures for each size fraction of carbon particles and Ea is activation energy.

$$Ri = A \exp [-Ea/RT] \quad (7)$$

where

Ri = Average initial rate for the three temperatures,

A = Frequency factor, R = Gas constant T = Absolute temperature and

Ea = Approximated activation energy.

The stripping of adsorbed gold cyanide from activated carbon is dependent on the strip solution composition; and this is clearly depicted in Table 18. In Table 18, the three stripping solutions used in the research have been compared on the basis of the amount of gold stripped with a 0.2L bed volume of the strip solution. The numbers without the brackets are for the amount of gold stripped in 0.2L of the stripped solution used while the numbers in brackets depict the total amount of gold stripped from gold-loaded carbons. In general based on the syringe pump and filter press methods the Davidson

strip solution (5% KOH and 10% K_2CO_3) was the most efficient solution, followed by the AARL solution (1% NaOH and 3% NaCN). The Zadra solution (1% NaOH and 0.5% NaCN) was the least efficient of the three solutions compared. It must be pointed out that, the reasons why the Davidson solution was more effective in the stripping process than the AARL and Zadra solutions were not determined, and so any attempt to assign reasons would be mere speculation. It is important that further work be done to determine these reasons.

In summary, it has been shown that the carbon particle size, temperature of the strip solution and the strip solution composition do, in an interdependent fashion, affect the stripping of gold cyanide from activated carbons. And to optimize the extent and amount of gold eluted, these factors must all be set at their proper levels.

3.5 Carbon-in-Leach (CIL) Experiments with MAC

To determine the possibility of using magnetic activated carbon, BMAC 27B to treat preg-robbing ores, carbon-in-leach (CIL) experiments with MAC were conducted with a preg-robbing ore from Newmont's Twin Creek Mine. As described in section 2.4, the as-received ore received (minus 850 μm particle size) was ground with lime addition to about 90% passing 38 μm. The prepared ore was then used for the CIL experiments. Three evaluation times (6, 12 and 24 hours) and three different weights of MAC (0, 3 and 6 g) were used for the experiments. After each CIL experiment, the MAC product (loaded with gold cyanide) was separated from the non-MAC material (ore tailings) by a Carpco wet high intensity magnetic separator. Solution samples taken during the experiments were analyzed at the Department of Metallurgical Engineering ICP-AES laboratory while

the MAC and non-MAC products were analyzed by fire assay at the analytical laboratories of the Newmont Mining Company.

The results are presented in Tables 20 to 23. Tables 20 and 21 show the distribution of gold for the 3 and 6 g BMAC 27B, experiments respectively. In each case gold distribution to the leach solution, the leached ore and the carbon is shown for 6, 12 and 24 hours experiments. The amount of gold in the leach solution was between 3 and 6% for the 6 and 12 hour experiments, and 11 to 19% for the 24 hour experiment. This suggests that either the amount of carbon, BMAC 27B was not enough in the leach solution to adsorb all the gold leached or that the adsorbed gold was desorbing into solution, particularly for the 24 hour experiment.

In Table 22, two values are presented for each leach time and amount (g) of MAC used respectively. The values in brackets represent the percent gold recovered using the two-product formula while the values without brackets represent percent gold distribution to the MAC as shown in Tables 20 and 21. The values in the brackets (obtained by two-product formula) should have been equal to the values without the brackets (obtained from back calculations). The differences between the two values in Table 22 are insignificant for the 6 and 12 hours CIL times. However, a 16 and 20 percent difference between the two values is estimated for the 24-hour leach time, for the two weights of MAC used. The difference is significant and can be attributed to experimental error.

It should be pointed out that in spite of the inconsistent values recorded for the 24-hour leach time in Table 22, BMAC 27B achieved 70% gold extraction from the preg-robbing ore in 6 hours, and this is very encouraging when compared with Table 23; which depicts the percent gold adsorbed by granular activated carbon (GAC) under

Table 20
CIL Gold Distribution for BMAC 27B (3 g), Preg-robbing Ore and Leach Solution.

Sample description	Weight [g]	Assay [mg/kg]	Weight [mg gold]	Distribution of gold [Percent]
6-hours 3 g MAC				
MAC product	3.00	17.185	0.052	64.09
Leach solution	100.00	0.050	0.005	4.93
Ore tailing	29.29	1.101	0.032	30.97
Total			0.089	100.0
12-hours 3 g MAC				
MAC product	3.00	19.621	0.059	65.58
Leach solution	100.00	0.030	0.003	2.69
Ore tailing	32.95	1.099	0.036	31.73
Total			0.098	100.0
24-hours 3 g MAC				
MAC product	3.00	25.052	0.075	57.44
Leach solution	100.00	0.150	0.015	11.49
Ore tailing	34.00	1.196	0.041	31.15
Total			0.131	100.0

Conditions: 3 g of BMAC 27B was added to 0.1L of leach solution and about 30 g of preg-robbing ore and leached for 6, 12 and 24 hours. Initial cyanide concentration was 1000ppm, pH = 11 and percent solids was 35.5.

Table 21
CIL Gold Distribution for BMAC 27B (6 g), Preg-robbing Ore and Leach Solution.

Sample description	Weight [g]	Assay [mg/kg]	Weight [mg gold]	Distribution of gold [Percent]
6-hours 6 g MAC				
MAC product	6.00	10.056	0.060	66.99
Leach solution	100.00	0.040	0.004	3.70
Ore tailing	30.10	1.098	0.033	29.31
Total			0.097	100.0
12-hours 6 g MAC				
MAC product	6.00	10.556	0.063	65.96
Leach solution	100.00	0.040	0.004	3.63
Ore tailing	31.50	1.092	0.034	30.41
Total			0.102	100.0
24-hours 6 g MAC				
MAC product	6.00	12.384	0.074	55.39
Leach solution	100.00	0.260	0.026	19.80
Ore tailing	31.90	1.055	0.034	25.78
Total			0.134	100.0

Conditions:6 g of BMAC 27B was added to 0.1L of leach solution and about 30 g of preg-robbing ore and leached for 6, 12 and 24 hours. Initial cyanide concentration was 1000ppm, pH = 11 and percent solids was 37.3.

Table 22
Gold Recovered from Preg-robbing Ore (Newmont Twin Creek Mine) by Magnetic Activated Carbon (BMAC 27B).

CIL Time [Hours]	Percent gold recovered on MAC	
	30 g MAC/L solution	**60 g MAC/L solution**
6-hours	64.1(67.4)	67.0(69.6)
12-hours	65.6(67.4)	66.0(68.4)
24-hours	57.4(64.8)	55.4(67.9)

Conditions: Percent solids in slurry sample used for WHIMS separation = 2, peristaltic stirrer speed and pump feed settings were 2.5 and 1 respectively. Slurry flow rate to WHIMS = 800 ml/min.; wet high magnetic intensity separator was set to low current range equal to a setting of 1.

Table 1
Percent Gold Recovered from Preg-robbing Ore (Newmont Twin Creek Mine) by Granular Activated Carbon using Four Cyanidation Methods (56).

Sample description	Percent gold recovered		
	0 g GAC/L	20 g GAC/L	40 g GAC/L
Baseline cyanidation	1.5	53.0	58.6
Cyanidation with blinding agent		60.6	63.7
Alkaline pressure oxidation	9.2	69.6	71.4
Acidic pressure oxidation	83.7	93.4	94.1
Chemical oxidation		75.4	78.7

various pretreatment conditions. In the case of the CIL experiments conducted with BMAC 27B, the only pretreatment given was grinding the preg-robbing ore to minus 38 μm and adjusting it to a suitable pH with lime. In the GAC experiments, the CIL results with MAC compare well with the baseline cyanidation test (ore was ground to minus 25 μm) and cyanidation with blinder addition test (diesel oil added to ground ore) in which the pretreatment of the preg-robbing ore was not pressure and temperature intensive.

The other three CIL results with GAC were pressure and/or temperature intensive. For example, in the alkaline and acidic pressure oxidation tests, pretreatment temperatures and pressures were 120/220°C and 130/440 psi, respectively. While in the chemical oxidation test, an elevated temperature of 80°C and hypochlorite were used (56). It is clear from the foregoing discussions that the CIL leaching conditions with BMAC 27B are only comparable to the baseline cyanidation tests with GAC in Table 23. Comparing the two, the results clearly show that the percent gold extracted with BMAC 27B from preg-robbing ore is comparable with the results of the alkaline pressure oxidation pretreatment of the pre-robbing ore in Table 23; which is very encouraging. These results in addition to the adsorption and elution rates results presented for BMAC 27B in the preceding sections suggest that BMAC 27B has the potential to replace GAC especially for the treatment of preg-robbing gold ores.

In summary, the ability of magnetic activated carbon, BMAC 27B, to compete with carbonaceous matter in preg-robbing gold ore has been shown by the CIL experiments with MAC. The adsorptive capability of MAC is demonstrated by attaining 70% gold recovery from preg-robbing ore in 6 hours without pretreatment compared with 55% reported for GAC (56). This in addition to previous results reported in the preceding

sections for MACs adsorption and desorption abilities certainly demonstrates that MAC has the potential to replace GAC for gold recovery, especially for the treatment of preg-robbing ores. However, it must be pointed out that the MAC technology needs to be further evaluated to determine if it can be regenerated and recycled. It is expected that the next step, in the development of MAC technology will be a pilot demonstration at the University of Utah's Department of Metallurgical Engineering.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Granular activated carbon (GAC) continues to be the favored route for gold recovery in cyanidation plants, yet gold losses on fine activated carbons and the attendant high carbon inventories are substantial and continue to be a problem. In light of this, one of the objectives of this thesis research has been to investigate the effect that particle size and other process variables (temperature, pressure and strip solution composition used for the stripping process) have on the adsorption and desorption of gold cyanide from traditional activated carbon (AC) and magnetic activated carbon (MAC). In addition, an emphasis of the research was to compare the elution rates of AC and MAC and discuss the nature of the elution reaction. The final objective of the thesis research was to investigate the possibility of using MAC to recover gold from preg-robbing ores. Consequently, four experimental techniques have been used to evaluate the effect of particle size, temperature and strip solution composition on the desorption of gold cyanide from AC/MAC. Furthermore, the elution rates of AC and MAC have been compared, and the possibility of using MAC to recover gold from preg-robbing ores has been determined.

Activated carbons from three different sources and a magnetic activated carbon, BMAC 27B, were used in the research. Barnebey AC was supplied by Newmont Mining Company while Calgon carbon and Calgon carbon GRC 22 were supplied by Eriez

Magnetics and Calgon Corporation respectively. The BMAC 27B was supplied by Eriez Magnetics while the preg-robbing ore for the CIL experiments was from Newmont's Twin Creek Mine.

The rate of adsorption results were consistent with the expectation that rate of adsorption is inversely dependent on particle size, as discussed in section 3.3. The first order reaction velocity constant values are consistent with what has been reported in the literature and reinforces the view that initial rate of gold adsorption may be controlled by film diffusion through mass transfer boundary layer or by surface reactions. The loading capacity values were found to vary from 29 to 39 kg Au/t C and are consistent with values reported in the literature.

The four stripping techniques used to evaluate the effect of particle size, temperature, pressure, and strip solution composition on the adsorption and elution of gold cyanide from activated carbons were atmospheric Zadra, syringe and hydraulic press, syringe pump, and filter press elution methods. The atmospheric Zadra elution method was studied under a batch mode without solution replacement (continuous-batch stripping) and with incremental solution replacement (batch-solution replacement stripping) methods at atmospheric pressure and elevated temperatures. However, in the other three stripping methods, pressure was employed to force strip solutions through a bed of carbon placed in a syringe or filter press.

Finally, the preg-robbing ore received was prepared and leached using a carbon-in-leach process with MAC after which the MAC product (concentrate) was separated from the non-MAC material (ore tailings) by a wet high gradient magnetic separator.

It has been substantiated from the experimental results that:

- The stripping reaction has an inverse dependence on activated carbon particle size
- The stripping reaction has a direct dependence on temperature
- The composition of the strip solution has an influence on the stripping reaction
- The magnetic activated carbon, BMAC 27B has a faster adsorption and desorption rate than the AC.

Particle size has an effect on the rate of elution of gold cyanide from AC. This expectation has been supported with results from three out of the four stripping methods used in the research. In the three pressurized stripping methods (syringe and hydraulic press, syringe pump and filter press), increased elution rate was observed for the finer AC. Elution of the coarser carbon, GAC, was slow. In fact, the rate and extent of elution data reveal that the rate and extent of gold elution from AC increases as the AC particle size decreases. These results are in contrast to the atmospheric Zadra elution method in which case elution from GAC was faster and more complete than was obtained with fine AC particles. It appears that in the stripping process, the stripping reaction may be controlled by pore diffusion, surface reactions, and or film diffusion depending on the size fraction of carbon being stripped. In this regard it is expected that the stripping reactions for the finer carbons may be controlled by surface reactions or film diffusion given its shorter diffusion distances, while the coarser carbons may be predominantly controlled by pore diffusion and/or surface reactions in view of longer diffusion distances. It can be concluded that, like the adsorption of gold cyanide on activated carbons, the stripping reaction is inversely dependent on particle size; and the stripping reaction may be controlled by pore diffusion, surface reaction, and or film diffusion.

High strip solution temperatures (98-100°C) tend to increase rate and extent of the stripping reaction. The temperature effect was demonstrated with the filter press elution method using Davidson strip solution at three different temperatures (25, 60 and 98°C). The rate of elution and the effect of temperature on elution demonstrate that as the temperature decreases from 98 to 25°C, the elution rate of reaction decreases significantly. At 25°C the elution is generally less than 10%. The temperature effect on the elution rate is further supported by the results presented for stripping with Zadra solution at room temperature and 80 psi pressure under the filter elution method. It was again observed in this instance that, even though an 80 psi pressure was applied during the stripping process less than 10% of the adsorbed gold on the carbons was eluted, thus supporting the notion that temperature is a most critical factor that controls the elution rate of gold cyanide from AC. Furthermore, the activation energy values for average initial rates were found to be about 20-36 KJ/mol, significantly lower than the 58KJ/mol value reported for stripping by Adams (6). The results seem to indicate that the stripping reaction may be controlled by a combination of pore diffusion, film diffusion and surface reactions. For example, if the rate were controlled exclusively by film diffusion, an activation energy of less than 20 KJ/mol would be expected.

The type of strip solution used in the elution process has been observed to have a significant influence on the stripping reaction. The efficiencies of the three strip solutions used in the elution experiments were evaluated. The Davidson strip solution (10% KOH and 5% K_2CO_3), was found to be the most effective in the stripping of gold cyanide from AC/MAC, followed by the AARL strip solution (1% NaOH and 3% NaCN), the Zadra strip solution (1% NaOH and 0.5% NaCN), is the least efficient in eluting gold cyanide

from carbon. It is important to point out that the Davidson strip solution was effective in stripping all the carbon samples (both the GAC and the sized carbon particles) of their adsorbed gold cyanide under the syringe pump method. In fact, all the carbons had nearly 100% of adsorbed gold cyanide eluted in 2 L of strip solution. However, this was not the case under the filter press elution method with the Davidson strip solution. The most plausible reason for the two outcomes is the fact that the filter press chamber (with solution retention time of less than a minute) was very large relative to the amount of gold-loaded carbon (3 g) been stripped, and as a result there was not enough pressure and solution hold-up in the filter press chamber to cause effective stripping to occur. In the syringe pump method, however, there was enough pressure and solution hold-up in view of the syringe chamber size (60 ml with a solution retention time of 3-4 minutes) relative to the amount of gold-loaded carbon stripped (1 g). This seem to suggest that if enough pressure can be built-up in the stripping chamber of an elution system, in addition to the fact that all the other interdependent factors are set at their correct levels, then probably all ACs irrespective of size can be eluted by the Davidson strip solution. Furthermore, the efficiency of the Davidson strip solution over the Zadra and AARL solutions, and its ability to strip all carbons irrespective of size suggests that it has the technical potential of replacing the two strip solutions (Zadra and AARL) for gold desorption applications in industry. Of course economic factors must be taken into consideration, and further work must be done to identify the factors that account for the effectiveness of the Davidson solution over the AARL and Zadra solutions.

The pressure effect on the rate of elution of gold cyanide can be inferred by comparing the results of atmospheric Zadra elution method to those of the other three

stripping methods. The results of the atmospheric Zadra elution favored the GAC while the other three pressurized elution methods favored the fine carbons. In addition, the fact that the finer activated carbons did not strip effectively at elevated temperatures using the atmospheric Zadra method, and yet achieved significant stripping results with the pressurized elution methods suggest that pressure may have played a role in the efficient stripping of the fine carbons. Furthermore, it has been shown by the atmospheric Zadra method that temperature alone will not drive the stripping reaction; and it has equally been shown by the filter press method using Zadra solution at 25°C and 80 psi pressure that pressure alone will not drive the desorption reaction. What this research has attempted to substantiate by the four stripping methods used is to demonstrate the fact that a number of factors (activated carbon particle size, temperature, pressure, and strip solution composition) interdependently drive the stripping reaction. In order to maximize the extent and amount of gold eluted from gold-loaded carbons the factors must all be set at proper levels; pressure is one of the factors. When the results of the four stripping methods are considered in concert, a conclusion can be drawn that pressure is a critical factor required to force presoaked gold out of the pores and surface sites of the carbons. If this were not true then effective stripping would have been achieved for all the carbons under the atmospheric Zadra stripping method.

The adsorption and elution rates of magnetic activated carbon, BMAC 27B, have been excellent. BMAC 27B consistently achieved gold adsorption rates of above 90% in the first 15 minutes of the adsorption experiments. Furthermore, BMAC 27B achieved nearly 100% stripping with the Davidson strip solution under the syringe pump and filter press elution methods. Finally, carbon-in-leach with MAC results for BMAC 27B have

also been encouraging. The rapid gold recovery of 70% recorded for BMAC 27B in 6 hours is certainly an improvement over recoveries of 55% that have been reported using GAC after 24 hours of leaching (56). This makes BMAC 27B an adsorbent which has the potential to replace GAC for gold recovery from preg-robbing ores.

In summary, it has been substantiated from this research that particle size, temperature, pressure, and the type of strip solution used in the elution process are factors that are interdependent in the influence they have on the elution of gold cyanide from AC and BMAC 27B. These factors must all be set at their proper levels in order to maximize the rate and amount of gold desorbed from loaded carbons. Finally, it has been shown that fine particles of BMAC 27B can be loaded and stripped with ease and that MAC has the potential to replace GAC for the treatment of preg-robbing gold ores. Work done by Munoz at the University of Utah's Department of Metallurgical Engineering showed that MAC has a rapid adsorption kinetics compared with GAC; and that when MAC is used in industry instead of GAC; it has the potential to reduce plant size (12, 28).

The results of this current research have reinforced the findings of Munoz. In addition, this research has substantiated that MAC has a rapid stripping rate compared with GAC and that MAC used in the carbon-in leach process for the treatment of preg-robbing ores can be cleanly and effectively separated by a wet high intensity magnetic separation process. Furthermore, it has been shown that MAC has a comparative advantage over GAC for the treatment of preg-robbing ores. While MAC can achieve 70% gold recovery in 6 hours from preg-robbing ores without pretreating the ore, previous results indicate that GAC can recover 55% in 24 hours. The next stage of the MAC technology must consider acid wash and regeneration capability of the MAC, after

which of course it seems, will be followed by a pilot plant demonstration at the University of Utah's Department of Metallurgical Engineering. In light of the results and discussions, it is clear that MAC could have distinct advantages over GAC if adopted by industry. It is expected that plant size might be reduced due to MACs fast adsorption and desorption kinetics. In addition preg-robbing ores might be treated without any pretreaments. Thus the use of MAC technology could provide improved technology for the gold industry.

APPENDIX

Table 24
Average Percent of Barnebey Carbon Attrited in 24 Hours.

Description	Sample A	Sample B
Mass of dry sample [g]	50	50
Expected mass of sample [g]	49.86	49.85
Actual mass of sample [g]	49.80	49.81
Difference between expected and actual mass [g]	0.06	0.04
Mass of filter paper and undersize of sample [g]	3.97	3.99
Mass of filter paper only [g]	3.83	3.84
Percent attrition of sample	0.28	0.30
Average percent attrited	0.29	

Table 25
Average Percent of Calgon Carbon (Eriez Magnetics) Attrited in 24 Hours.

Description	Sample A	Sample B
Mass of dry sample [g]	50	50
Expected mass of sample [g]	49.85	49.84
Actual mass of sample [g]	49.79	49.78
Difference between expected and actual mass [g]	0.06	0.06
Mass of filter paper and undersize of sample [g]	3.94	3.96
Mass of filter paper only [g]	3.79	3.80
Percent attrition of sample	0.30	0.32
Average percent attrited	0.31	

Table 26
Average Percent BMAC 27B Attrited in 24 Hours.

Description	Sample A	Sample B
Mass of dry sample [g]	50	50
Expected mass of sample [g]	49.91	49.89
Actual mass of sample [g]	49.87	49.82
Difference between expected and actual mass [g]	0.04	0.07
Mass of filter paper and undersize of sample [g]	3.90	3.92
Mass of filter paper only [g]	3.81	3.81
Percent attrition of sample	0.18	0.22
Average percent attrited	0.20	

Table 27
Average Percent Calgon GRC 22 (Calgon Corporation) Attrited in 24-Hours.

Description	Sample A	Sample B
Mass of dry sample [g]	50	50
Expected mass of sample [g]	49.48	49.45
Actual mass of sample [g]	49.39	49.37
Difference between expected and actual mass [g]	0.09	0.08
Mass of filter paper and undersize of sample [g]	4.27	4.30
Mass of filter paper only [g]	3.75	3.75
Percent attrition of sample	1.04	1.11
Average percent attrited	1.08	

Calculation for Gold Adsorption Rate (%)

Percent gold adsorbed = [(A – B)/ A] x 100 (8)

where:

A = Initial gold concentration in solution

B = Gold concentration after time, t

Table 28
Rate Calculations.

Time [minutes]	Gold concentration in solution [mg/L]	Gold adsorbed on carbon [mg]	Percent gold adsorbed
0	13.43	0	0
15	0.95	12.54	93
30	0.25	13.24	98
45	0.16	13.33	99
60	0.11	13.38	99

Calculations for Gold Adsorption Capacity

Applying the Freundlich equation;

$$\text{Log } [X / M] = \text{Log } K + 1/n\text{Log } C \quad (9)$$

where:

X = Mass of gold adsorbed after 24 hours

M = Mass of carbon used

C = Equilibrium concentration of gold

K = Carbon loading constant (mg Au/g C or kg Au/t C)

Gold loading after 24 hours is given by:

$$X = [(Au_i - Au_f) \times V_s]/ M \quad (10)$$

where:

X = Mass of gold adsorbed after 24 hours

Au_i = Initial gold concentration in solution

Au_f = Gold concentration at equilibrium

V_s = Volume of gold solution used

Table 29
Adsorption Capacity Calculations.

	C [ppm Au]	X [mg Au]	M [g]	X/M [kg Au/t C]
Initial concentration	114.12			
0.1	57.01	5.7	0.10	57.1
0.2	25.96	8.8	0.20	44.1
0.3	9.25	10.5	0.31	33.8
0.4	2.1	11.2	0.41	27.3
0.5	0.06	11.4	0.51	22.4

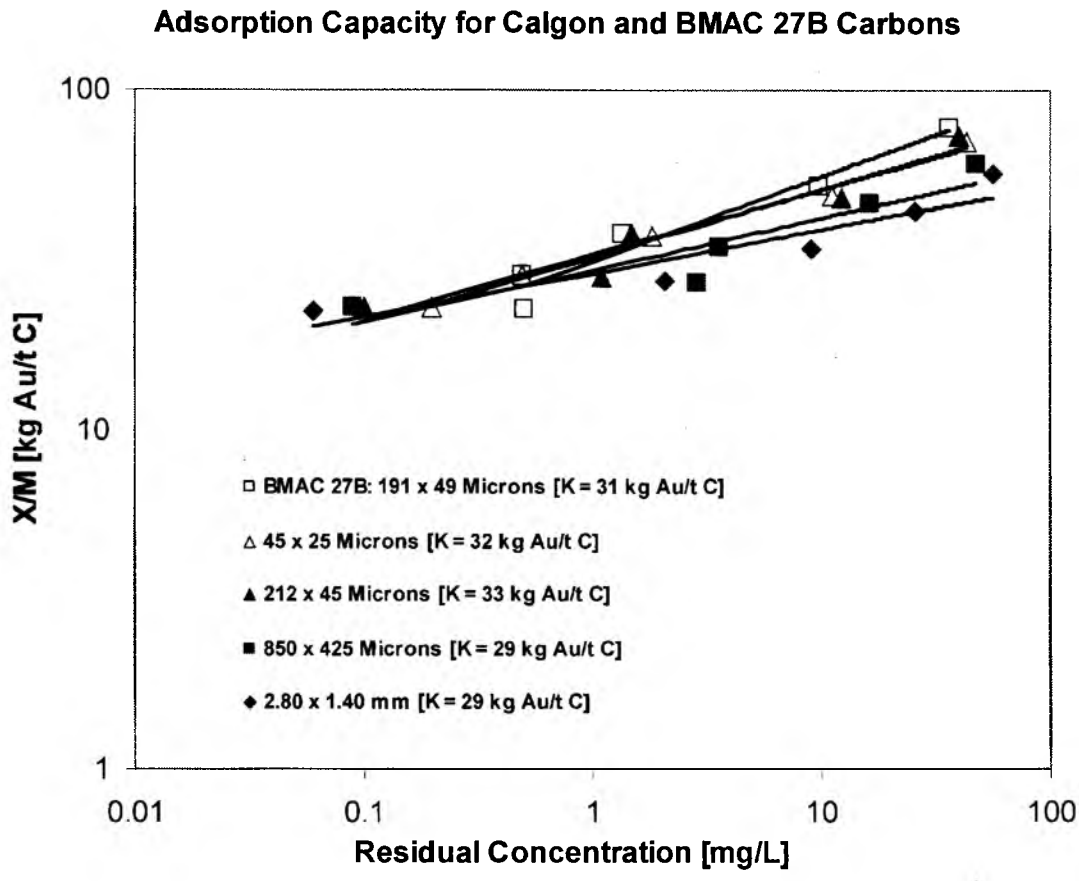


Figure 33 Loading Capacities for Calgon and BMAC 27B Carbons (Eriez Magnetics).
Loading conditions: Carbon samples of different weights were loaded with 100 ml of 114.12 mg Au/L solution at pH = 10.41, 25°C, rpm = 200 for 24 hours.

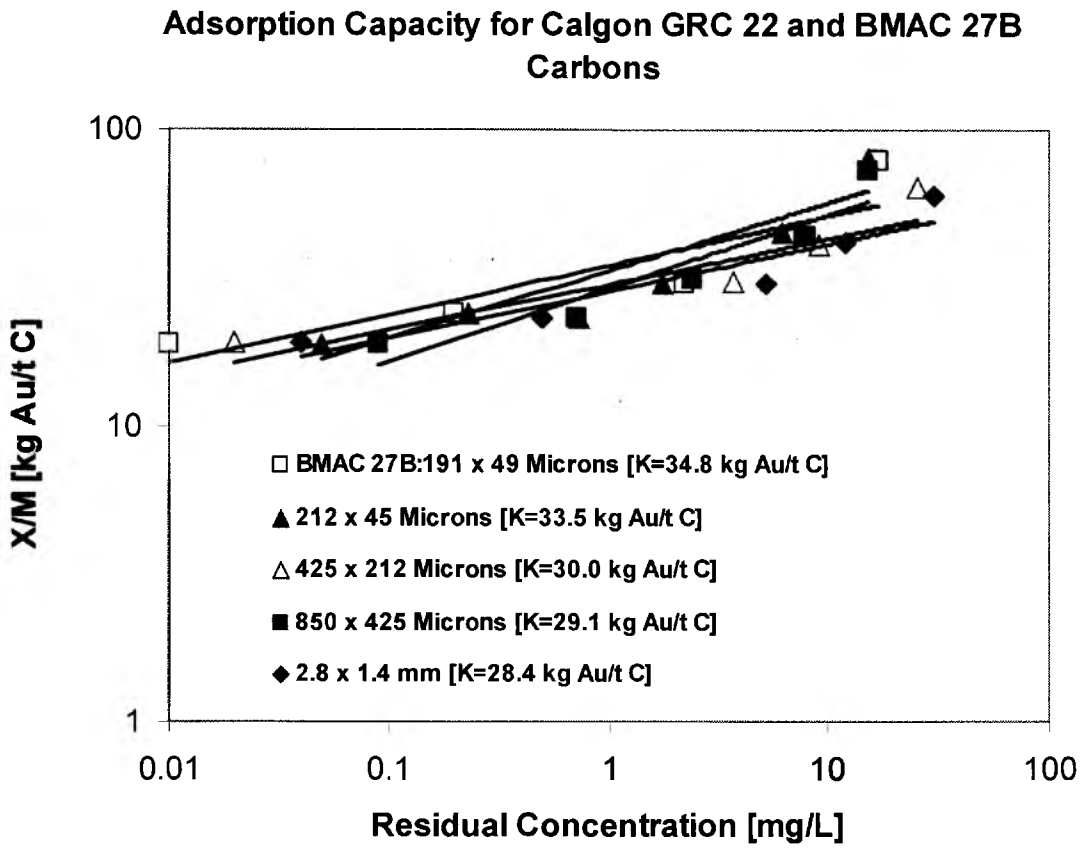


Figure 34 Loading Capacities for GRC 22 Carbon (Calgon Corporation) and BMAC 27B (Eriez Magnetics).
Loading conditions: Carbon samples of different weights were loaded with 100 ml of 98.63 mg Au/L solution at pH = 10.10, 25°C, rpm = 200 for 24 hours.

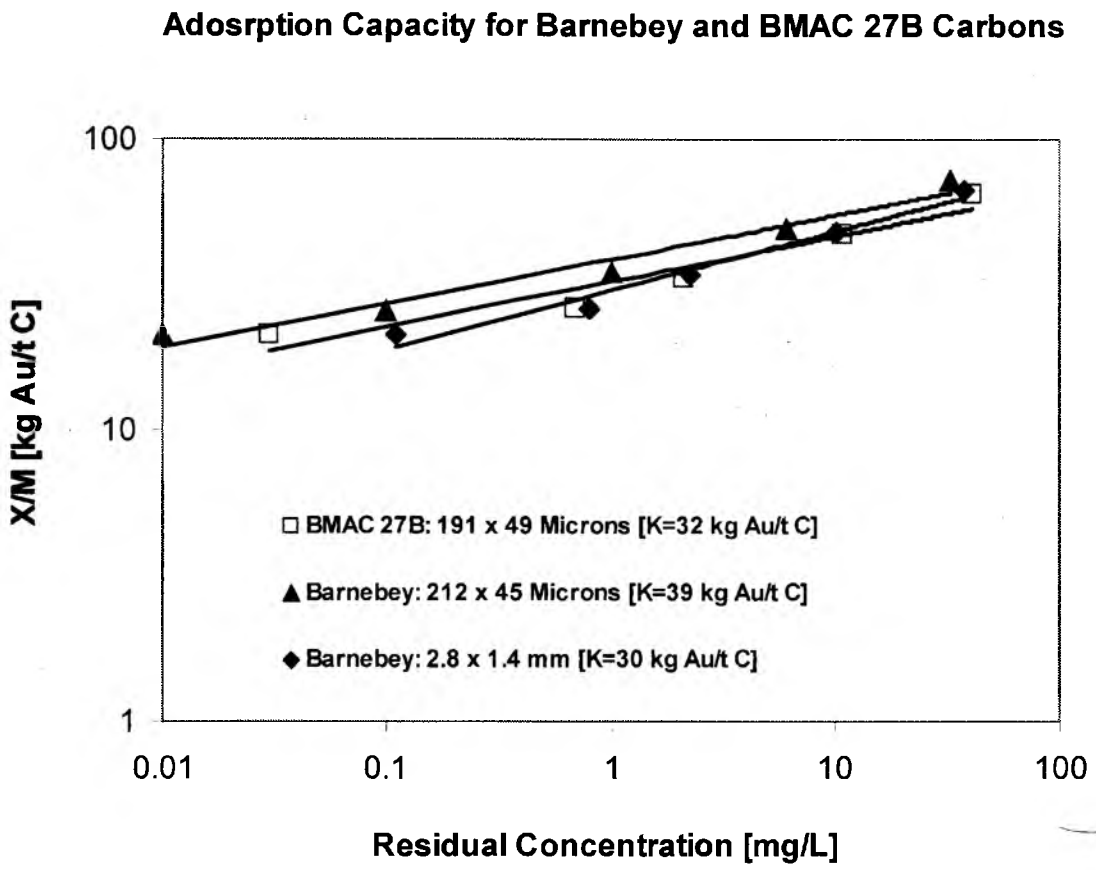


Figure 35 Loading Capacities for Barnebey AC (Newmont Mining) and BMAC 27B Carbons (Eriez Magnetics).
Loading conditions: Carbon samples of different weights were loaded with 100 ml of 105.35 mg Au/L. solution at pH = 10.41, 25°C, rpm = 200 for 24 hours.

Calculations for Gold Elution Rate

Percent gold eluted was calculated using equation 8:

$$\text{Percent gold eluted} = [(A - B)/A] \times 100 \quad (11)$$

where: A = Gold on carbon before elution and B = Gold on carbon after elution

Table 30
Gold Elution Rate Calculations.

Time [hours]	Gold conc. in solution [mg/L]	mg Au eluted	Percent gold eluted
0	**0**	0	**0**
0.5	**260.61**	**130.3**	**55**
1	**270.82**	**132.7**	**56**
2	**272.85**	**131.0**	**55**
4	**272.16**	**127.9**	**54**
8	**277.56**	**127.7**	**54**
12	**253.54**	**114.1**	**48**
24	**218.84**	**96.3**	**40**

Solution Dilution Formula

$$C_iV_i = C_fV_f \quad (12)$$

where: C_i and C_f = Initial and final concentrations

V_i and V_f = Initial and final volumes

Magnetic Activated Carbon-in Leach Calculations

Initial NaCN Concentration [1000ppm]

Number of moles = [0.75/49.0072] = 0.0153

Molarity = [0.0153 moles/ 0.1 L] = 0.1530M

Hence we have [0.1530 moles/L x 0.1 L x 49.0072g] = 0.7498g NaCN in 0.1L leach solution.

Titration Solution Preparation

Silver Nitrate [$AgNO_3$]

0.1 M $AgNO_3$ was made

3.4g/169.87g = 0.200 moles

0.2 L $AgNO_3$ was prepared

Molarity = 0.0200 moles/ 0.2 L = 0.1 M

Potassium Iodide [KI] indicator

0.2 M KI was made

3g/166.01g = 0.01807 moles

Molarity = 0.01807 moles/ 0.1 L = 0.1807

0.2 L KI was prepared.

Initial NaCN Concentration [1000ppm] from Titration

Number of moles = [2 g/49.0072 g/mole] = 0.0408 moles

Molarity of 0.1 L = [0.0408 moles/ 0.1 L] = 0.408M

We have [0.408 mole/L x 0.1 L x 49.0072 g/moles] = 2 g NaCN in 0.1 L leach solution.

From Table 31, the initial NaCN concentration before leaching is determined as follows:

Average volume of $AgNO_3$ used = 60/3 = 20 ml

Molarity of NaCN on 0.01L = [0.1 x 20]/ 10 = 0.2 M

Number of moles of NaCN in 0.01L = 0.2 moles/L x 0.01L = 0.0.002 moles

Number of moles of NaCN in 0.1L = 0.2 moles/L x 0.1L = 0.02 moles

Grams of NaCN in 0.1 L of initial leach solution = 0.02 moles x 49.0072 g/mole = 0.980g

Table 31
Titration to Determine Initial NaCN Concentration before Leaching Experiments.

Readings	1	2	3
2nd Reading [ml]	20.01	40.00	20.00
1st Reading [ml]	0.00	20.01	0.00
Volume of AgNO3 used [ml]	20.01	19.99	20.00

Table 32 is used to determine the NaCN concentration in the leaching system after 6 hours:

Average volume of $AgNO_3$ used = 30.40/ 3 = 10.13 ml.

Molarity of NaCN on 0.01L = [01 x 10.13]/ 10 = 0.1013 M

Number of moles of NaCN in 0.01L = 0.1013 moles/L x 0.01 L = 0.001013 moles

Number of moles of NaCN in 0.1L = 0.1013 moles/L x 0.1 L = 0.01013 moles

Grams of NaCN in 6g MAC sample after 6 hours = 0.01013 moles x 49.0072 g/mole = 0.4964g

We have 500 ppm or 0.5 g of NaCN in 0.1 L leach solution after 6 hours of leaching. Therefore 300 ppm and 600 ppm of NaCN were added to the 12 and 24 hours samples respectively.

Table 32
Titration after 6 Hours of Leaching to Determine NaCN Concentration (6 g MAC).

Readings	1	2	3
2nd Reading [ml]	10.10	20.20	30.40
1st Reading [ml]	0.00	10.10	20.20
Volume of AgNO3 used [ml]	10.10	10.10	10.20

Table 33 is used to determine NaCN concentration in the leaching system after 24 hours:

Average volume of $AgNO_3$ used = 25.98/2 = 12.99 ml.

Molarity of NaCN on 0.01L = [0.1 x 12.99]/10 = 0.1299 M

Number of moles of NaCN in 0.01L = 0.1299 moles/L x 0.01 L = 0.001299 moles

Number of moles of NaCN in 0.1L = 0.1299 moles/L x 0.1 L = 0.01299 moles

Grams of NaCN in 6g MAC sample after 24 hours = 0.01299 moles x 49.0072g/mole = 0.637 g or 637 ppm of cyanide was present in 6 g MAC sample after 24 hours of leaching.

Table 33
Titration after 24 Hours of Leaching to Determine NaCN Concentration (6 g MAC).

Readings	1	2
2nd Reading [ml]	13.00	25.98
1st Reading [ml]	0.00	13.00
Volume of AgNO3 used [ml]	13.00	12.98

Percent (%) Solids Calculation

Percent [%] Solids in Grinding

[1000g/2500g] x 100 = 40%

Percent [%] Solids in Leaching

100 ml of DI-water used for all samples.

For 0 g MAC

[50/150] x 100 = 33.3%

For 3 g MAC

[53/153] x 100 = 35.0%

For 6 g MAC

[56/156] x 100 = 36.0%

Dilution for WHIMS Separation

For 3 g MAC

[53/2553] x 100 = 2.1%

For 6 g MAC

[56/2556] x 100 = 2.2%

Strip Solution Calculations

Zadra Solution [1% NaOH and 0.5% NaCN]

1% NaOH:

1% NaOH → 100 g/100 ml

1% NaOH in 1 L→ [1 g NaOH/100 ml] x [10/10] = 10 g NaOH/ 1000 ml = 10 g NaOH/L

0.5% NaCN:

0.5% NaCN → 0.5 g/100 ml

0.5% NaCN/L→ [0.5 g NaCN/100 ml] x [10/10] = 5 g NaCN/L

Davidson Solution [10% KOH and 5% K_2CO_3]

10% KOH:

10% KOH → 10 g/100 ml

10% KOH/L → [10 g KOH/100 ml] x [10/10] == 100 g KOH/L

5% K_2CO_3:

5% K_2CO_3 → 5 g/100 ml

5% K_2CO_3 L → [5 g K_2CO_3/100 ml] x [10/10] = 50 g K_2CO_3/L

AARL Solution [1% NaOH and 3% NaCN]

1% NaOH:

1% NaOH → 100 g/100 ml

1% NaOH in 1 L → [1 g NaOH/100 ml] x [10/10] = 10 g NaOH/ 1000 ml = 10 g NaOH/L

3% NaCN:

3% NaCN → 100 g/100 ml

3% NaCN/L → [3 g NaCN/1oo ml] x [10/10] = 30 g NaCN/L

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